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ASSESSMENT OF HUMAN THERMAL SENSATIONS BASED ON BIOCLIMATIC INDICES IN A SUBURBAN POPULATION, WROCŁAW (SW POLAND)

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K e y w o r d s: thermal perceptibility scale, temporal distribution, effective temperature, radiative-effective temperature.

A b s t r a c t

The aim of this study was to characterize thermal sensations and distribution across the years 2006–2011 on the basis of two bioclimatic indicators. The study was based on hourly meteorological data for the period April-October collected from the station, located on the eastern outskirts of Wrocław. TE and TRE were calculated with the use of BioKlima 2.6. software, while the evaluation of thermal sensations by the local population was performed according to the scale developed by Mikhailov. The average TE in the period April-October was 8.3°C and on average about 1.1°C lower than TRE. The highest TE and TRE were recorded in the summer months. In July, their above-average levels were most frequently reported between 9:00 and 17:00. During the 7-month-long study period, all kinds of thermal sensations were reported; from „very cold" to „hot". In suburban Wrocław, sensations of „cold" dominated. „Hot" temperatures were indicated only by TRE in four months.

OCENA ODCZUĆ CIEPLNYCH CZŁOWIEKA W WARUNKACH PODMIEJSKICH WROCŁAWIA NA PODSTAWIE WSKAŹNIKÓW BIOKLIMATYCZNYCH, POLSKA POŁUDNIOWO-ZACHODNIA

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S ł o w a k l u c z o w e: skala odczuwalności cieplnej, rozkład czasowy, temperatura efektywna, temperatura radiacyjno-efektywna.

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Abstrakt

Celem pracy była charakterystyka rozkładu czasowego w latach 2006–2011 i ocena odczuć cieplnych człowieka na obszarze podmiejskim Wrocławia. W pracy wykorzystano godzinne dane meteorologiczne w okresie kwiecień–październik, zebrane ze stacji Państwowego Monitoringu Środowiska, położonej na wschodnich peryferiach Wrocławia. Wartości wskaźników TE i TRE obliczono w programie BioKlima 2.6, natomiast ocenę odczuć cieplnych człowieka przeprowadzono wg skali opracowanej przez Michajłowa. Średnia temperatura TE w okresie kwiecień-październik wynosiła 8.3°C i była przeciętnie niższa, o 1.1°C, od temperatury TRE. Najwyższe wartości obu rozpatrywanych wskaźników notowano w miesiącach letnich – czerwiec-sierpień. W lipcu ponadprzeciętne, dodatnie wartości rozpatrywanych wskaźników notowano najczęściej w godzinach 9:00–17:00. W rozpatrywanym okresie wystąpiły wszystkie rodzaje odczuwalności cieplnej człowieka od „bardzo zimno" do „gorąco". W warunkach podmiejskich Wrocławia dominują odczucia zimna o różnym nasileniu w każdym z badanych miesięcy przez większą część doby. Na wystąpienie odczucia gorąca wskazał tylko wskaźnik TRE w czterech miesiącach w badanym okresie, od maja do sierpnia.

Introduction

The inhabitants of large cities are exposed to thermal stress that is usually greater than in adjacent rural areas (UNGER 1999, FORTUNIAK et al. 2006, NDETTO and MATZARAKIS 2013, MAJEWSKI et al. 2014). This adverse effect is additionally exacerbated by air pollution, noise, and the intense pace of life in the city, which increases susceptibility to various diseases, especially among the elderly (DUBICKI et al. 2002, SARRAT et al. 2006, KALBARCZYK and KALBARCZYK 2007, JOHNSON and WILSON 2009, BURKART et al. 2011, RASZKA et al. 2014). This is one of the reasons behind the decision to move out of the city in search of better living conditions (BASU and SAMET 2002, GABRIEL and ENDLICHER 2012, LAAIDI et al. 2012). Polish cities are no exception; in the 2000s they saw a construction boom in the suburbs and adjacent rural areas (with a peak in 2008) and a rapid outflow of residents from the city centers. However, the increased intensity of settlements surrounding the cities may contribute to the deterioration of inner thermal conditions. This hypothesis can be partially verified by the determination and comparison of thermal perceptibility in suburban areas with the previously known conditions in the city center (SZYMANOWSKI 2005, SIKORA 2008). The specific aim of this research was to analyze the temporal distribution of thermal sensations by the population in suburban areas of the city of Wrocław. Our analysis were based on effective temperature (TE) and radiative-effective temperature (TRE), the basic indicators of thermal perceptibility commonly used in bioclimatic research (MAKOKHA 1998, TEJEDA-MARTINEZ and GARCIA-CUETO 2002, WERESKI and WERESKI 2009, PÓŁROLNICZAK 2011, CZERNECKI and PÓŁROLNICZAK 2013).

Materials and Methods

The study used hourly meteorological data for the period from April to October, from the National Environmental Monitoring Station (PMS) in Wrocław belonging to the Lower Silesian Inspectorate for Environmental Protection, located in Wrocław, in Bartnicza Street (λ=17°08'28"E, φ=51°06'58"N, hs=120 m above sea level, code – PL0193A), across subsequent years 2006–2012 (Fig. 1). The data included air temperature (t, °C), relative humidity (f, %) at about 2 m agl and wind speed (v, m s^{-1}) at about 10 m agl. The station is located on the eastern outskirts of the city, the Psie Pole district, at the premises of the Swojec Agricultural Experimental Station, approx. 8 km from the center of Wrocław. The measuring point is surrounded by single-family houses and farmland, with no industrial areas nearby. Any missing values of global solar radiation (Kglob, W m^{-2}) were supplemented by measurements from the station located in Wrocław-Karłowice (λ=17°01'46"E, φ=51°07'46"N, hs=121 m above sea level) located in Korzeniowskiego Street.

Station of the NEM	Longitude	Latitude	Elevation [height above sea level]	Type of area
Wrocław – Bartnicza	17°08'28" E	51°06'58" N	120	suburban

Fig. 1. Location of the national environmental monitoring station (NEM) in Wrocław

Meteorological data collected for consecutive years across the multiannual period 2006–2012 were used to assess human thermal sensations based on two indicators: effective temperature (TE) and radiative-effective temperature (TRE). TE is known as quasi temperature, describing the combined effect of three elements: t, f and v on the human thermal comfort of a man dressed in simple summer clothes and performing light work (eg. walking) under shade. The TRE index, in addition to the three meteorological elements (t, f and v), also takes into account an additional element – Kglob. The TRE index defines human thermal sensations in the open air in direct sunlight. Before determining TE and TRE, the wind speed was reduced to a level of 2 m above the ground level by the following formula (KRAWCZYK 1991, PÓŁROLNICZAK 2011):

$$v_z = v_w(h_z/h_w)^{0.2}$$

where
v_z – wind velocity at a height of 2 m (m s^{-1}),
v_w – wind velocity at the height of measurement (m s^{-1}),
h_z – target height (m),
h_w – measurement height (m).

TE ratios and TRE were calculated based on positive air temperatures using the procedure implemented in the BioKlima 2.6 software, developed and then made available for research by BŁAŻEJCZYK (2004):

$$TE = t - 0.4 \cdot (t - 10.0) \cdot (1 - 0.01 \cdot f), \text{ when } v \leq 0.2 \text{ m s}^{-1} \text{ or}$$

$$TE = 37 - \frac{37 - t}{0.68 - 0.0014 \cdot f + \frac{1}{1.76 + 1.4 \cdot v^{o}\ 75}} - 0.29 \cdot t \cdot (1 - 0.01 \cdot f)$$

when $v > 0.2$ m s^{-1}.

The lower wind velocity limit in the formulas used in the BioKlima 2.6. software is based on the assumption that the movement of air below 0.2 m s^{-1} is experienced as no air movement.

TRE was determined according to the formula developed by BŁAŻEJCZYK (2004):

$$TRE = TE + (1 - 0.01 \cdot ac) \cdot Kglob \cdot [(0.0155 - 0.00025 \cdot TE) - (0.0043 - 0.00011 \cdot TE)]$$

where
t – air temperature (°C),
f – relative humidity (%),
v – wind speed (m s^{-1}),
Kglob – global solar radiation (W m^{-2}),
ac – albedo of the human skin or clothing (assumed to be 31% in this paper).

The evaluation of thermal sensations on the basis of TE and TRE was conducted according to the scale developed by Mikhailov (cited by BŁAŻEJCZYK 2004), in which temperature intervals correspond to thermal sensations (Table 1).

Temporal distribution of TE and TRE was characterized on the basis of basic statistics; arithmetic mean ($\bar{x}$) and standard deviation (Sd) by month for the period April-October in both the entire multiannual period and in individual years. The study also involved the incidence of individual human thermal sensations based on the Mikhailov scale (cited by BŁAŻEJCZYK 2004) in different time steps (day, week and month).

Table 1

The scale of human heat perceptibility by Mikhailov (cited by BŁAŻEJCZYK 2004)

Class of temperature (°C)	Impact on the human body
<1	very cold
1–8.9	cold
9–16.9	cool
17–20.9	fresh
21–22.9	comfortable
23-26.9	warm
≥27	hot

Results and Discussions

Across the period 2006–2011, in suburban Wrocław the average daily effective temperature (TE) for the period April-October was 8.3°C (Table 2). Radiative-effective temperature (TRE) in the examined seven-month period was higher than TE, on average by 1.1°C. The largest differences between the TRE and TE were recorded in June (1.4°C) and then in July and April (1.3°C). Much greater differences between the temperatures were found for measurements at 12:00. Moreover, in the studied years in the period from April to October, the average TE at 12:00 was about 1.5°C lower than the daily average in the same period for Wrocław in the multiannual period 1981–2000 (SIKORA 2008). This difference may be due to the considerable distance of the study area from the center of Wrocław (approx. 8 km). The studies by DUBICKI et al. (2002) confirm the presence of an urban heat island in Wrocław – its average annual intensity in the hottest central area of the city ranges from 0.5°C (in the day) to 1.6°C (at night). The influence of the urban heat island in Wrocław can be felt even at a distance of 5.5 km from the center, even though its average intensity is low, from 0.1°C (in winter) to 0.6°C (in summer, at night).

In all the examined months TRE at noon was higher than TE, in April by as much as 3.5°C. Of course the clearly higher noon TRE than TE can be explained by the intense inflow of solar radiation. In turn, TE at 12: 00, with the exception of April, was lower in the following months than in the multiannual period 1981–2000 (SIKORA 2008), especially at the end of the analyzed period, ie. in September and October, by as much as 2.5–2.7°C.

Table 2

Mean ($\bar{x}$) and standard deviations (Sd) of TE and TRE by month. Years 2006–2011

Month	TE index				TRE index			
	$\bar{x}$		Sd		$\bar{x}$		Sd	
	24 hours	12:00	24 hours	12:00	24 hours	12:00	24 hours	12:00
April	3.2	6.5	6.0	5.2	4.5	10.0	6.9	5.8
May	7.3	10.1	5.9	6.0	8.4	13.4	6.7	6.8
June	11.4	14.2	5.4	5.2	12.8	17.4	6.1	5.8
July	13.7	16.4	5.5	5.5	15.0	19.7	6.3	6.1
August	12.5	15.2	4.7	4.7	13.6	18.1	5.4	5.3
September	7.7	10.0	5.4	5.4	8.6	13.2	6.0	6.1
October	2.3	5.0	5.6	5.9	2.9	6.7	5.9	6.3

24 hours – the average of 24 measurements, 12:00 – measurement at noon

The standard deviation of TRE compared to TE was greater in all the analyzed months.

Temporal distributions of TE and TRE – by month in consecutive years – were similar to the distribution of air temperature; the maximum recorded in the summer months, from June to August (Fig. 2). Similarly, the presence of the highest average TE and TRE in July is confirmed by other studies, including those conducted in Wroclaw, Wielkopolska and north-eastern Poland (CHABIOR and MICHALSKA 2007, SIKORA 2008, SZYGA-PLUTA 2011). The standard deviation determined for the individual months and years, similar to the multiannual period (Table 2), was about 0.3–1.1°C higher for TRE than TE.

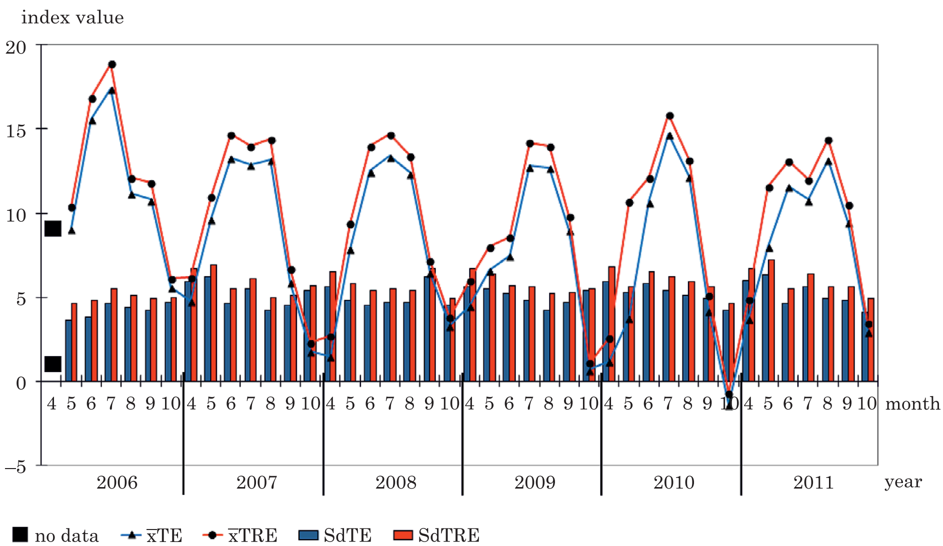


Fig. 2. Mean ($\bar{x}$) and standard deviations (Sd) of TE and TRE by month and year

The values of the aforementioned indices varied depending on the month and time of day (Fig. 3). In the summer months across the years 2006–2011, the highest TE was primarily recorded in the hours 10:00–18:00 in the period from 1st decade of July to 2nd decade of August, and in the hours of 8:00–20:00 in the 2nd decade of July. Higher ranges, were observed for longer time for TRE between 9:00 and 17:00 in the period June-August, and from 7:00 to 20:00 in the 2nd decade of July. The values in the range of 20–25°C of TRE were observed at 10:00–15:00 in the 2nd decade of July. In the night, in the time between sunset and sunrise, in the absence of solar radiation, TRE had the same values as the TE in the range 5–10°C, both ratios occurring mostly from 0:00–5:00.

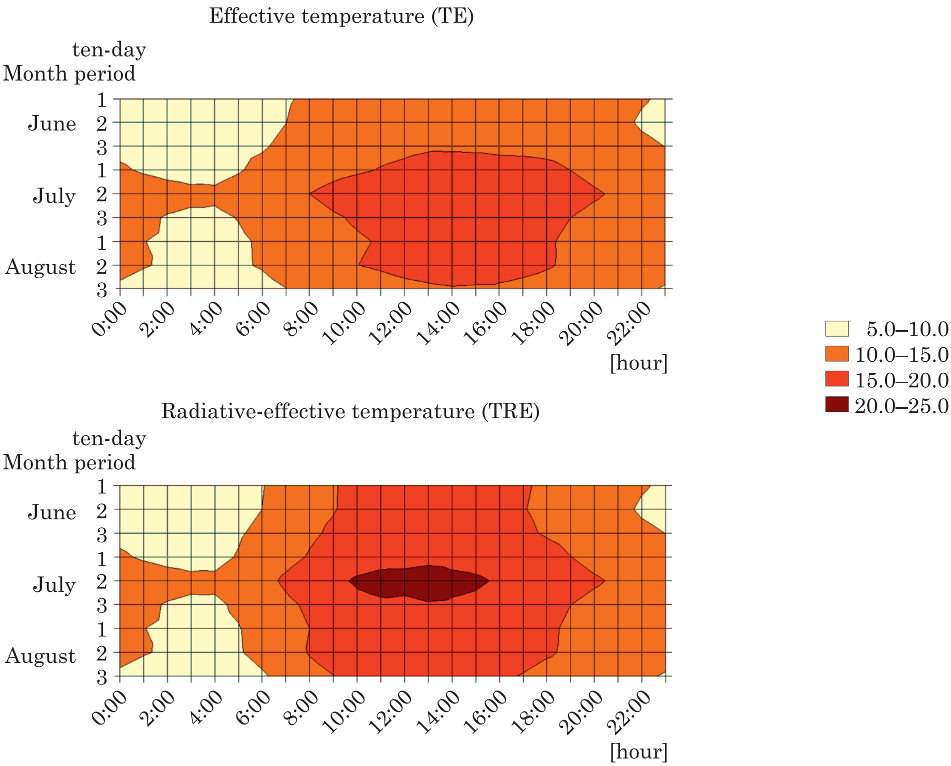


Fig. 3. Temporal distribution of average decade TE and TRE in the period June-August by hour in the analyzed multiannual period (2006-2011)

An analysis of the distribution of mean daily TE and TRE, by summer month and by year, shows that the number of days with TE≥15°C averaged about 9 and 13 days, respectively for two indicators, the highest number in July, the lowest in June (Fig. 4). The greatest number of days in July with the

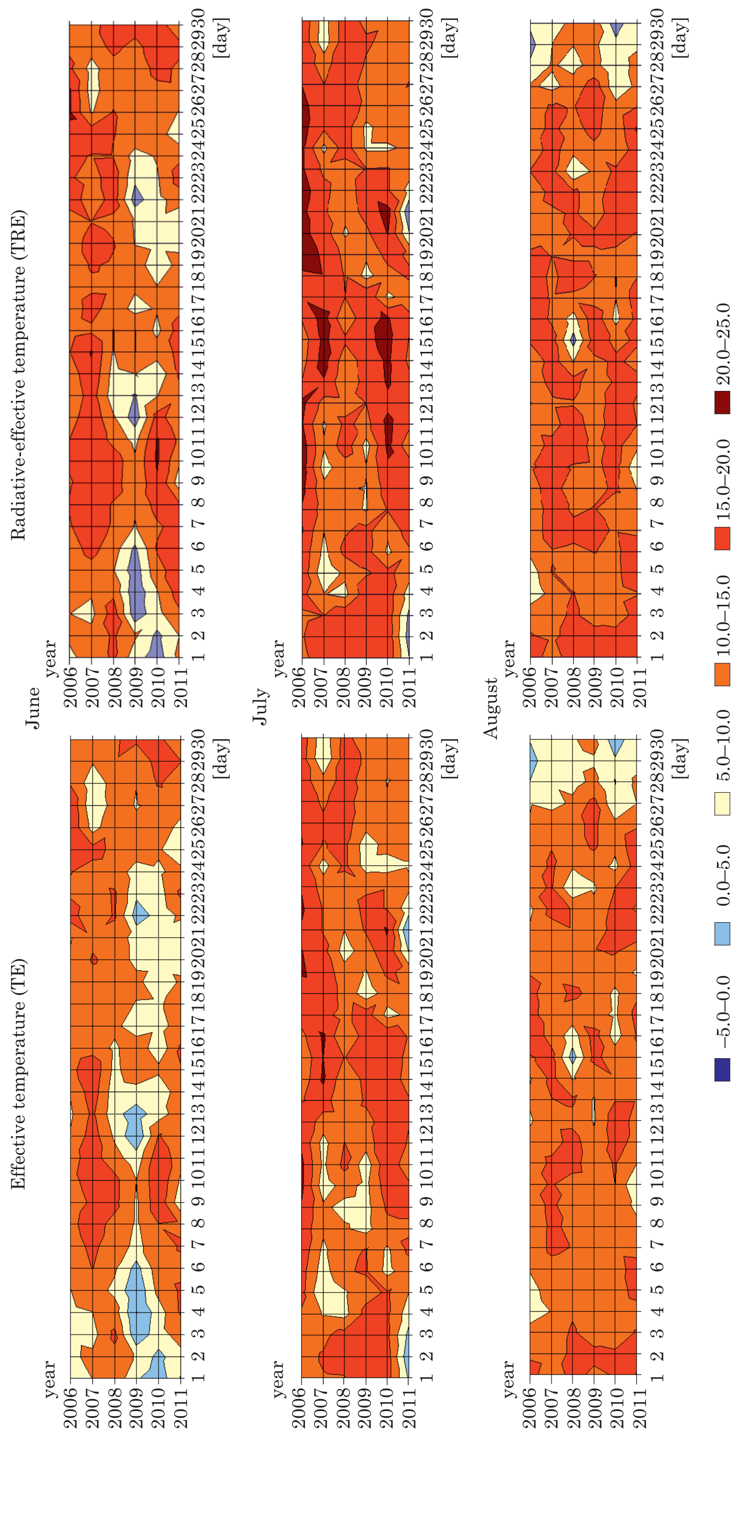


Fig. 4. Distribution of daily average TE and TRE by months and years

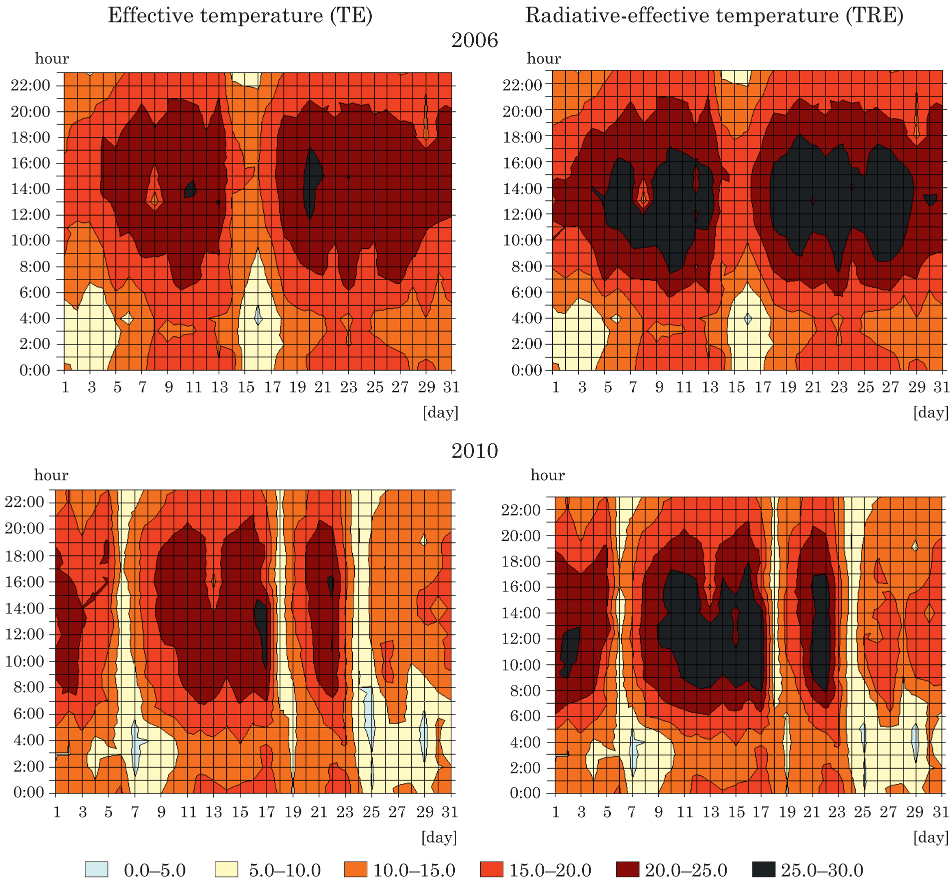


Fig. 5. Distribution of hourly average values of TE and TRE in July

mean daily temperature ≥15°C were recorded in 2006 and 2010 – 23 and 17 days for TE with 26 and 20 days for TRE, respectively. Temperatures ≥20°C occurred on average on 1 day for TE and 2 days for TRE, and on 6 and 14 days, respectively, in July 2006. TE and TRE <0°C occurred occasionally, on 1 day of each summer month.

In the months with the highest TE and TRE, i.e. in July 2006 and July 2010, the temporal distribution was similar (Fig. 5). In July 2006, from 11:00–18:00, the TE≥20°C generally occurred for 20–24 consecutive days broken by a 4-day period. The TRE≥20°C and the TRE≥25°C in July 2006 occurred for longer periods than TE during the day and for a greater number of days in the month. Lower temperatures of TE≤10°C and TRE≤10°C were recorded primarily at 0:00–5:00. In July 2010, the TE≥20°C and TRE≥20°C were reported primarily from 7:00–19:00 for about 10 days, the TE≥25°C was recorded for 2 days and TRE≥25°C for 12 days. In contrast to 2006, TE≤10°C in

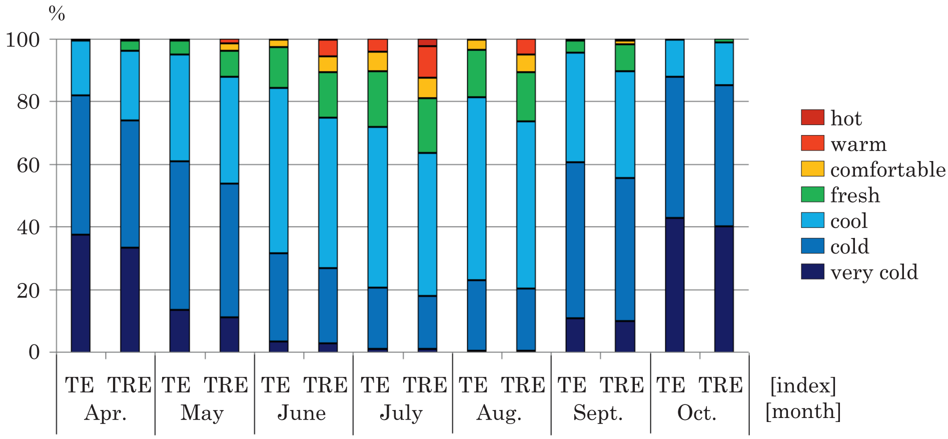


Fig. 6. The frequency of human thermal sensations determined on the basis of TE and TRE in the analyzed multiannual period (2006–2011), by month

2010 was recorded not only at night and early morning, but also in the daytime.

During the period from April to October, and in the analyzed multi-annual period, all types of heat sensations on the Mikhailov scale had been reported, i.e. from „very cold" to „hot" (Fig. 6). TE had been reported as „comfortable" in only the three months, and for TRE this period was two months longer. A „comfortable" TE and TRE was reported in July, then in August and June, similar to other studies in Wrocław and Wielkopolska (SIKORA 2008, SZYGA-PLUTA 2011). A „comfortable" TRE was also recorded occasionally in May and – even less frequently – in September. The observed low incidence of comfortable conditions is consistent with the opinion on the higher frequency of climatic stimulation in suburban areas than in the city center (DUBICKI et al. 2002).

The coldest TRE conditions, „very cold", were reported in April-July and September-October, most frequently in October, then in April. Cool and cold sensations were reported with a similar frequency for TE and TRE. The differences between the TE and TRE gained in significance for the warmest conditions. Sensations described as „hot" were reported only for TRE and in only one month. The sensation of „warm" was reported in five months (TRE) or in one month (TE). The period April-October, which constitutes the warm season in Poland, was therefore dominated by sensations of cold. The most common among these were the sensations of cool, cold and then very cold temperatures. The next – in terms of occurrence – was the sensation of fresh temperatures, which ranged from 1% (April for TE and October for TRE) to 18% (July for TE and TRE). Definitely less frequent were the feelings of warm

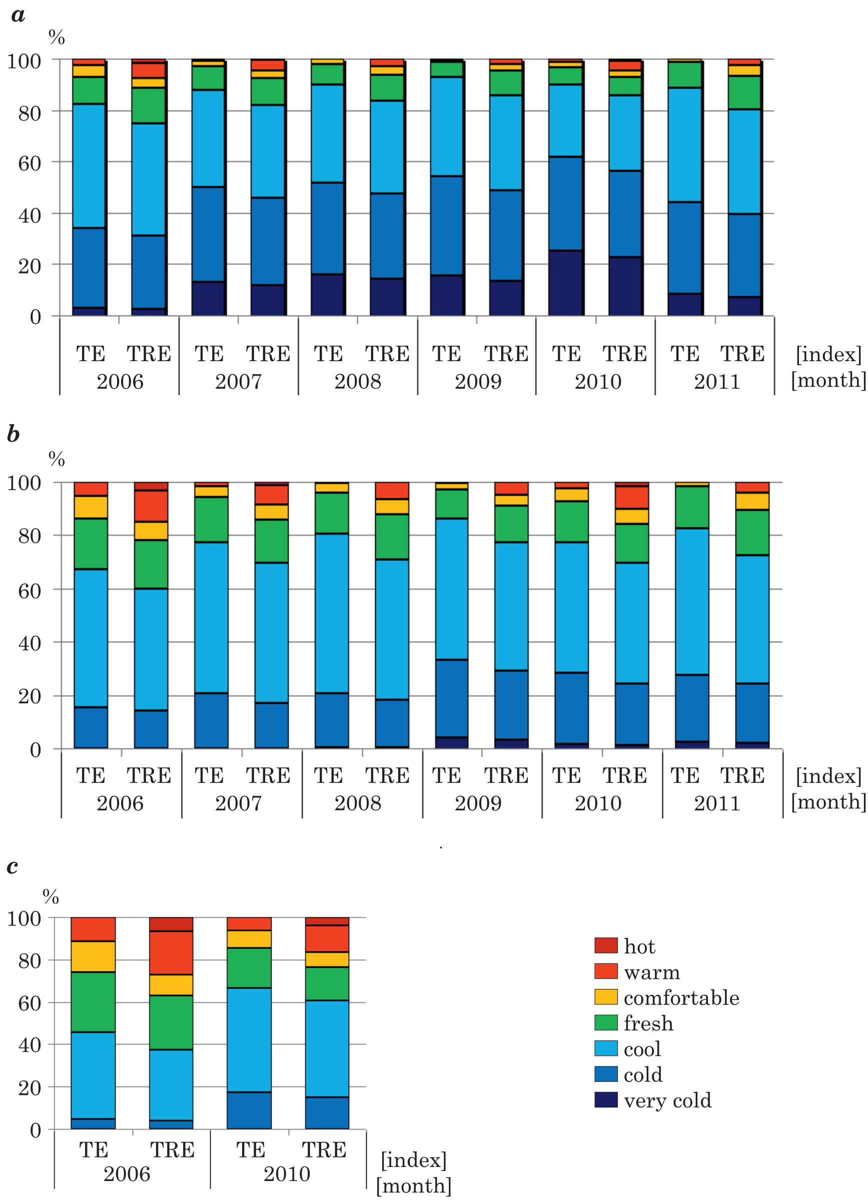


Fig. 7. The frequency of human thermal sensations determined on the basis of TE and TRE, by period and year; *a* – in the period April-October; *b* – in the period June-August; *c* – in July

temperatures (comfortable, warm and hot). Comfortable temperatures occurred a maximum of 6% of days in the month (July). In total, the various sensations of warm were reported for a maximum of 18% days (for TRE) of the hottest month of the year, i.e. July. A twice lower incidence of sensations of warm and hot temperatures on the outskirts of the city compared with the city center confirms the results of DUBICKI et al. (2002).

In the period April-October „very cold" sensations were most often reported in 2010 (>20% days), while least often in 2006 (approx. 3%) (Fig. 7a). Cold sensations of varying severity (from very cold to cool) occurred in each of the years of the multiannual period. The most common were the sensations of „cool", which – with the exception of 2010 – occurred on average 36–44% days (TRE) or 38–48% (TE) days a year. The sensation of „fresh" temperatures occurred most frequently in 2006 and the least frequently in 2009. Thermal comfort conditions were most often reported in 2006 (approx. 4.5% days) (TE) and 2011 (TRE), while least often in 2009. Warm temperatures were reported most frequently in 2006, and least often in 2009 (TRE) and 2008 (TE). The occurrence „warm" was reported only for TRE. It was the least frequently occurring sensation in each of the years, its frequency not exceeding 2%. In total, sensations of warmth at varying severity (comfortable-warm-hot) occurred most frequently in 2006, and least often in 2009.

In the period June-August the sensation of cold with varying severity was reported on 60% of days (TRE) and 67% of days (TE) in 2006 to 86% (TRE) and 77% of days (TE) in 2009 (Fig. 7b). The sensation of „very cold" temperatures occurred sporadically. Similar to the longer period of April-October, the period of June-August was dominated by the sensation of cool temperature, with an incidence of 46–60% days. The sensation of „fresh" temperature occurred relatively frequently, almost 20% days in 2006, the least often in 2009. Sensations from „comfortable" to „hot" occurred on less than 2% of days to 22% of days. Hot temperatures (TRE) were reported only in three years (2006, 2007 and 2010). In terms of TE, a comfortable temperature was the warmest sensation in two of the years, 2008 and 2011.

In July 2006 and 2010, the sensation of „very cold" temperature did not occur (Fig. 7c). The most common was the sensation of „cool" temperature, especially in 2010. In 2010 the sensation of „cold" temperature was more frequent, even 3–4 times than in 2006. The second most common sensation was „fresh" temperature, especially in 2006. In July 2006, the sensation of „warm" temperature was relatively frequent, more than „comfortable" temperature (TRE). The occurrence of hot temperature was shown only for TRE, for 7% days in July 2006, while for 4% days in July 2010. No sensation of „hot" temperature was reported in terms of TE. „Comfortable" temperature was more frequently reported in 2006.

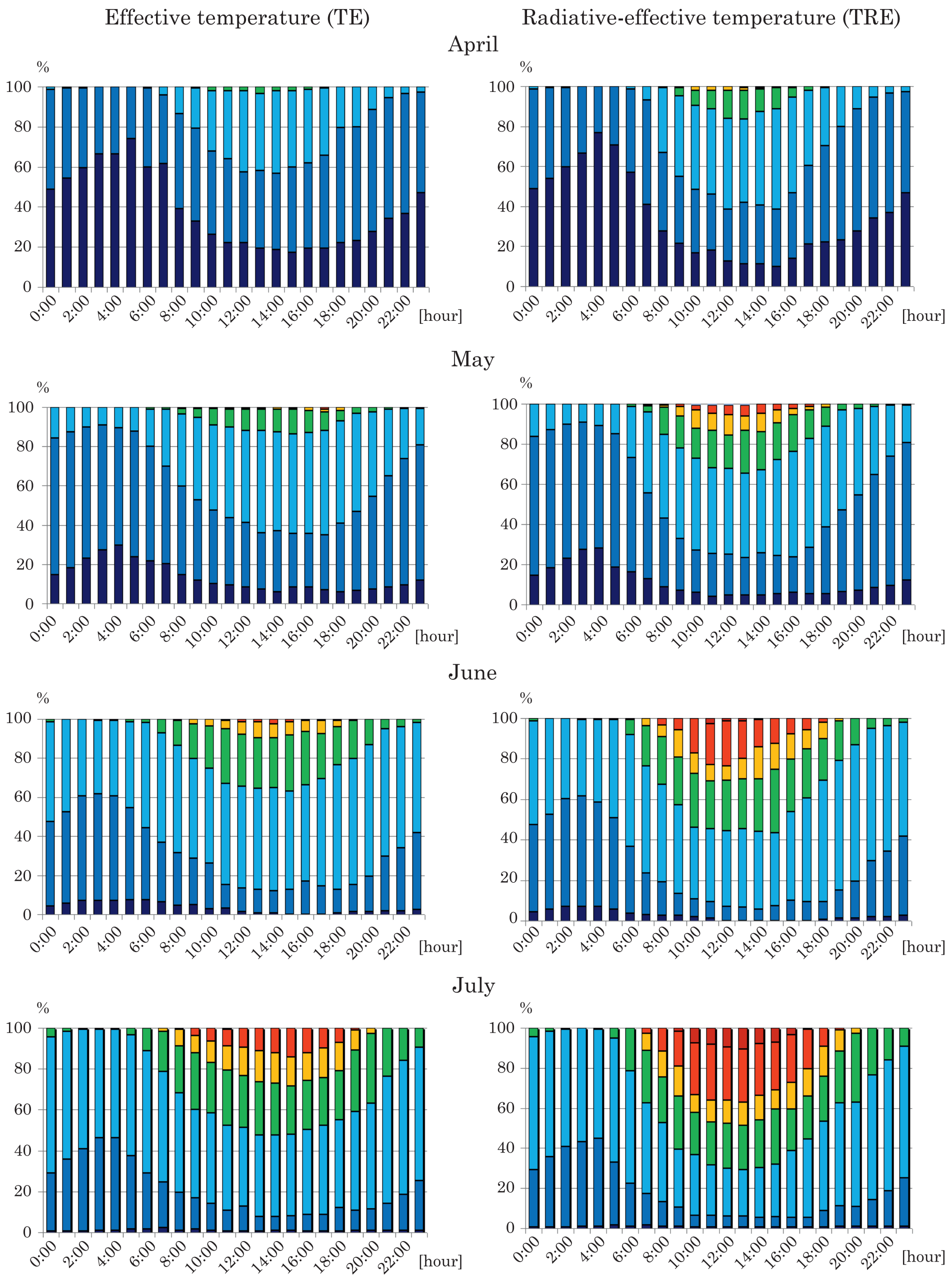
In hourly terms, it can be confirmed that the sensations of cold with varying degrees dominated in Poland, in this case it was reported in each of the studied months for most of the day (Fig. 8). The coolest hours of the day were in the morning: in the spring and early autumn (April-May) at approx. 4:00–5:00, in the summer (June-August) at approx. 3:00–4:00, in the fall (October) at approx. 5:00–6:00. The sensation of „very cold" temperature was experienced at least once in each hour of the day in the months of April, May, July and September. The sensation of „cold" occurred in each of the months, similar to the sensation of „cool" temperature, with the only exception of April in hours 3:00–5:00. The sensation of „fresh" temperature occurred on average from an entire day in July to 6–7 hours in October. „Comfortable" was rarely reported, from 13 hours a day in July to three hours a day in October. The sensation of „warmth" did not occur in October (in terms of TE it also did not occur in September), and only for one hour on average, between 13:00 and 14:00 in April, but for 11–12 hours in July. Hot temperature was only indicated by TRE in the four months during the period: May, June, July and August. The greatest frequency of hot temperature (10–12%) was reported in the hours 13:00–14:00.

The bioclimatic conditions in the suburbs are considered to be more beneficial to people than in the centers of large cities. In the summer, the urban heat island strengthens the sensation of hot temperature and is a strong burden for the human thermoregulatory system. Because of the smaller number of frosty and ground frost days in spring, autumn and winter, the city center contributes to a reduced thermoregulatory efficiency (DUBICKI et al. 2002). The positive aspect of the heat island is a lower risk of overcooling during the winter season, but this season was not covered in this research.

The used indicators of thermal conditions provide a description of thermal sensations of the inhabitants of the suburbs of Wrocław. At the same time, they represent a point of departure for further research with the use of more complex and comprehensive indicators of bioclimatic conditions (LI and CHAN 2000, BŁAŻEJCZYK et al. 2012, SZYMANOWSKI and KRYZA 2012, MAJEWSKI et al. 2014).

Conclusions

In suburban Wrocław, in the years 2006–2011, the courses of the effective temperature (TE and TRE) were characterized by a great diversity not only during the day, but also during the month and the entire analyzed period of April-October. TRE showed a greater variability in terms of the standard deviation in all months of the entire period, both on an annual and multian-


Effective temperature (TE)
Radiative-effective temperature (TRE)
April
May
June
July
%
0
20
40
60
80
100
0:00
2:00
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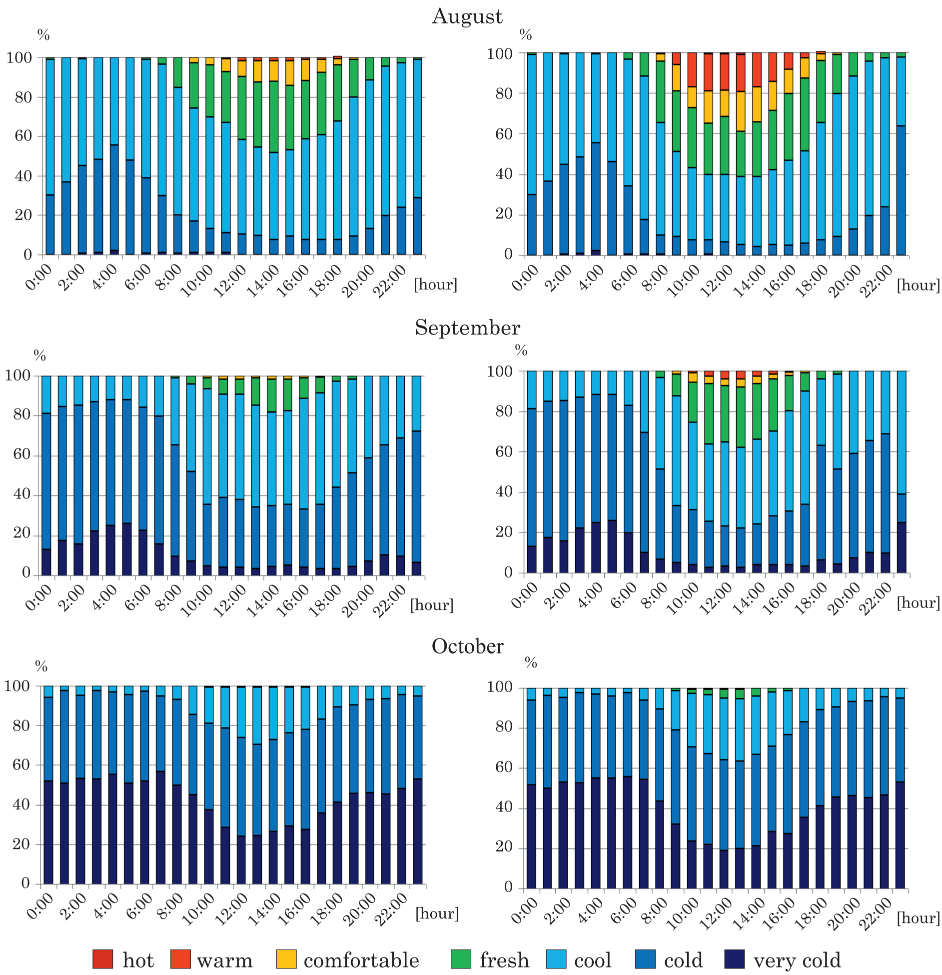

Fig. 8. The frequency of human thermal sensations determined on the basis of TE and TRE in the analyzed multiannual period (2006–2011), by month and hour

nual basis. In the period from sunrise to sunset, TRE was clearly higher than TE, which can be explained by the difference in solar radiation. During the period from April to October, all thermal sensations from the Mikhailov scale were reported (from „very cold" to „hot"), which indicates a significant climatic stimulation in the area.

The bioclimatological indicators TE and TRE used to evaluate the thermal sensations differed in indications. TE showed „very cold" to „fresh" sensations 2% more often than TRE, while TRE indicated „comfortable" to „hot" sensations 1.5% more often. Extremely adverse human thermal sensations in the period were recorded in October, mostly at night with „very cold”, and in July around noon for „hot”.

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