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RECENT TRENDS ON HUMAN THERMAL BIOCLIMATE CONDITIONS IN KYIV, UKRAINE

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Abstract

The human-biometeorological conditions in Kyiv (Ukraine) and changes in the frequency of heat stress during the summer period due to recent climate trends were analyzed. The evaluation based on physiologically equivalent temperature (PET). The results revealed the highest probability of thermal comfortable conditions in Kyiv is from the last 10-day period of April to the end of June and from the last 10-day period of August to the end of September. The probability of heat stress reached nearly 90% during the second and third 10-day periods of July. A pronounced increase in thermal stress during the studied heat wave cases (HW), as well as increasing amount of days with heat stress in the period 1991-2015, were found.

Key words

human thermal comfort • physiologically equivalent temperature • Kyiv • heat wave • heat stress

Introduction

The number of people who live in big cities continues to increase worldwide, as well as in Kyiv. Together with a growth of city size, big changes in environment components occur both within a city itself and in its suburbs. The increased use of man-made materials (with low albedo values) and increased anthropogenic heat production, which lead to changes in urban energy balance, are the main causes of urban heat island (UHI). The extent of this well-known atmospheric phenomenon also depends on the latitude and the size of the city (Tam, Gough, Mohsin, & 2015; Oke, 1978; Van Hove et al., 2015; Landsberg, 1981). The intensity of UHI in different cities can vary dramatically and sometimes at night can manifest with urban temperatures 10-15°C greater than those recorded in surrounding rural areas (Lokoshchenko, 2014; Landsberg, 1981; Tam et al., 2015; Sharma & Joshi, 2014). The UHI existence, wind speed reduction, and associated changes in urban energy balance within the city lead to the formation of specific bioclimatic conditions in urban areas. Also, these changes could be associated with more frequent events and the stronger influence of heat stress on city residents during warm periods, compared to the inhabitants of rural areas. Thus, people who live in big cities are exposed to heat waves (HWs) more often (Gabriel & Endlicher, 2011; Matzarakis, De Rocco, & Najjar, 2009; Fouillet et al., 2006). The combination of specific urban bioclimate and air pollution modifies the urban environment creating potentially more harmful conditions for its residents and can be the reason for high morbidity and mortality rates.

Due to recent climate trends most of the world's population has become more vulnerable to heat stress. In recent decades, observed climate trends show an increase in air temperature across Europe (IPCC, 2014), as well as in Ukraine (Balabukh & Lukianets, 2015). According to Shevchenko (2017) the average annual air temperature over the period 1991--2015 in Kyiv has increased by 1.2°C compared to the 1961-1990 (baseline) average. During the 1991-2015 period July mean air temperature increased by 2.1°C, maximum air temperature by 2.1°C and minimum air temperature by 1.6°C. It is well-known that air temperature is one of four meteorological parameters used in the estimation of human thermal perception. Matzarakis (2006), Matzarakis and Amelung (2008) showed that for climate change conditions the changes based on human biometeorological parameters, will be much higher than air temperature changes.

Investigations of human bioclimate and thermal comfort are usually conducted using bioclimatic or thermal indexes (Matzarakis, 2007). The first bioclimatic indexes were developed about 100 years ago and they were very simple. Physiologically equivalent temperature (PET) is a thermal index derived from the human energy balance. The basis for the PET calculation is "The Munich energy balance model for individuals" (MEMI) (Höppe, 1999). Compared to other bioclimatic indexes, which are also based on the human energy balance, PET has the advantage of being expressed in a widely known unit (degrees Celsius), which makes results more comprehensible to urban or regional planners or other people who are not so familiar with human-biometeorological terminology (Matzarakis, Mayer, & Iziomon, 1999). A comprehensive review of approaches and methods of outdoor human thermal perception conducted by Potchter, Cohen, Lin, and Matzarakis (2018) has shown that PET is amongst the four most widely used human thermal indices, noting that 165 have been developed. Other thermal indices do not have so many assessments worldwide (Matzarakis, 2007; Lee, Holst, & Mayer, 2013). An analysis of the frequency of the thermal indices that were used in the reviewed studies shows that PET was used in 30.2% of the case studies, predicted mean vote (PMV) was used in 10.1%, and universal thermal climate index (UTCI) and standard effective temperature (SET*) – in 8% and 5%, respectively (Potchter et al. 2018). Thus, as a widely used index PET facilitates the comparison of thermal bioclimatic conditions in different parts of the world. As proof that PET is suitable for the aim of the thermo-physiologically assessment of the human thermal environment, PET has been selected for the new VDI (Verein Deutscher Ingenieure) guideline (Staiger et al., 2019).

Nowadays, there has been much interest in the study of human thermal comfort in outdoor environments. The majority of such research has focused on human thermal sensations within urban areas. These studies include detailed examinations of thermal bioclimate in various urban structures mainly limited to the warm season (Lee et al., 2013; Andrade & Alcoforado, 2008; Matzarakis

& Mayer, 2003; Ali-Toudert & Mayer, 2006; Mayer et al., 2009; Hirashima, Assis, & Nikolopoulou, 2016). Additionally, there are a lot of successful attempts to make a human-biometeorological assessment of UHI (Zahradníček, Žák, & Skalák, 2014; Ketterer & Matzarakis, 2014), as well as estimates of thermal stress during HW periods (Konstantinov, Varentsov, & Malinina, 2014; Matzarakis et al., 2009; Matzarakis & Nastos, 2011b). The results of bioclimatic studies are very important for urban planning and architecture, as well as for decision-making processes and energy management of every city. Also, bioclimatic information may be successfully applied in the tourism sector to reduce economic loses and the negative effects of weather and climate on people during recreation period (Matzarakis, 2010). Therefore, characteristics of all-year thermal bioclimatic conditions and long-term analysis of changes of bioclimatic index values should be done for every city, not only because of the benefits of deeper scientific understanding, but also because of the important practical relevance for policy and planning across a number of sectors. The research of bioclimatic conditions in all months of the year on the basis of PET was conducted for Odesa (Ukraine) by Katerusha and Matzarakis (2015), for Budapest (Hungary) by Kovács and Németh (2012), as well as for Paris, Rome and Budapest based on the UTCI by Idzikowska (2010).

Research into the bioclimatic conditions of Kyiv was conducted in the 1970s-1980s by Eisenschtadt and Sakali (Osadchyi, Kosovets, & Babichenko, 2010). During this period the evaluation of city bioclimate was based on very simple indices, which are not based on the human energy balance and rely on only a few meteorological parameters for their calculation. Such indices are still used in almost every bioclimatic research of the territory of Ukraine. Obviously, these indexes are very simple to calculate, but the obtained results cannot fully represent real thermal stress on humans.

The aims of this work are an assessment of the human-biometeorological conditions in Kyiv during the year based on the human biometeorological parameter, PET and to analyze changes in frequency of heat stress occurrence during the calendar summer due to recent climate trends.

Study area and data

Kyiv (50°27´N, 30°31´E), located in the northern part of Ukraine, is the biggest city in the country (Fig. 1). It is situated on the banks of the Dnipro (Dnieper) river with an average elevation of 179 m above sea level. The city's administrative boundaries cover a total terrestrial area of approximately 850 km^2. The population of the city is about 3 million (not including non-permanent residents).

According to Köppen-Geiger's climate classification, Kyiv has a warm-summer humid, continental climate. Annual average sunshine duration is 1952 h. The annual average air temperature is 8.0°C. Total annual precipitation amount is 641 mm. The mean air temperature of the calendar summer (June–August) is 19.0°C (Osadchyi et al., 2010). The bioclimatic conditions of Kyiv in modern period were analyzed by using daily data (air temperature and relative humidity, wind velocity and cloud cover) between 2005 and 2014 at 12.00 UTC obtained from the observing station Kyiv of the Ukrainian Hydrometeorological Centre. Meteorological station Kyiv is situated in open space within the city area, but not in the city center. There is some distance from the station to nearest trees and buildings, thus this site is characterized by relatively homogeneous conditions. Observations conducted at the station are not automated. Observational instruments and methods to gather meteorological parameters are consistent with WMO requirements: ordinary (station) a mercury-in-glass-type thermometer for measurements of air temperature, a psychrometer for air humidity and propeller anemometers have been used to determine wind speed. Measurements of cloudiness have been made by visual observation.

Daily data in the summer months June to August for the period 1961-2015 (measured

Figure 1. Kyiv location

at the same time – 12.00 UTC) were used to determine changes in bioclimate of Kyiv in the modern period (1991-2015) compare to normal climatic period (1961-1990). Time series of daily maximum air temperature in the summer months June to August from 1961 to 2015 was used for determination of heat wave cases in Kyiv according to the definition recommended by the Intergovernmental Panel on Climate Change (IPCC).

The results of big cities thermal comfort conditions researches based on the data from a few meteorological stations situated within the city have shown differences of PET values between the city centers and suburbs (Zahradníček et al., 2014; Kovács & Németh, 2012). A lot of research shows significant differences in thermal bioclimate of various urban structures (Lee et al., 2013; Andrade & Alcoforado, 2008; Matzarakis & Mayer, 2003; Ali-Toudert & Mayer, 2006; Mayer et al., 2009; Hirashima et al., 2016). It is commonly known that such differences exist within urban areas because of the specific microclimatic conditions in different parts of the city. The results of the latest study of thermal regime differences between Kyiv and its suburbs (based on the data from meteorological stations) has shown the highest values of such differences reached 4°C, but in most cases, it is lower than 1°C (Shevchenko, Samchuk, & Snizhko, 2012). However, the air temperature values within Kyiv have been not always higher compare to suburbs during the research period (2004-2008). According to the data measured at the meteorological stations, the most pronounced UHI occurs at night and in the early morning. Thereby, it is clear that in the different types of urban structures of Kyiv bioclimatic conditions also have to be different, but, unfortunately, research to validate this hypothesis has not been conducted to date. Since, as mentioned earlier, the aim of this research is a complex assessment of the human-biometeorological conditions during the year and analysis of long-term changes in human thermal bioclimate, we therefore used daily data at 12.00 UTC measured at meteorological station Kyiv. However, it would be interesting to investigate differences in thermal bioclimate of Kyiv in various urban structures in the future.

Methods

The physiologically equivalent temperature is applied to the assessment of bioclimatic conditions in present research. PET values between 18.1 and 23.0 can be characterized as comfortable (Tab. 1).

Table 1. Ranges of the physiologically equivalent temperature (PET) for different grades of thermal perception by human beings and physiological stress on human beings (Matzarakis et al., 1999)

PET °C	Thermal perception	Grade of physiological stress
<4.0	Very cold	Extreme cold stress
4.1–8.0	Cold	Strong cold stress
8.1–13.0	Cool	Moderate cold stress
13.1–18.0	Slightly cool	Slight cold stress
18.1–23.0	Comfortable	No thermal stress
23.1–29.0	Slightly warm	Slight heat stress
29.1–35.0	Warm	Moderate heat stress
35.1–41.0	Hot	Strong heat stress
>41.1	Very hot	Extreme heat stress

The calculation of PET is performed utilizing the RayMan model (Matzarakis et al., 2007, 2010). The mean radiant temperature and physiologically equivalent temperature are simulated by RayMan using meteorological parameters, information about surface morphological conditions of the study area and personal parameters as input data. In this study the simulations referred to standard parameters of a person: 35-year-old man, 1.75 m high, 75 kg weight, wearing clothing with a heat resistance of 0.9 clo, sedentary, with heat producing is equivalent to 80 W.

The RayMan model has been broadly applied worldwide in different investigations on human-biometeorology, for instance in Germany (Matzarakis & Endler, 2010), Poland (Błażejczyk & Matzarakis, 2007), Nigeria (Omonijo et al., 2013), Egypt (Hassaan & Mahmoud, 2011), Greece (Matzarakis & Nastos, 2011a), China (Lin & Matzarakis, 2011), Hungary (Gulyás & Matzarakis, 2009), Brazil (Abreu-Harbich, Labaki, & Matzarakis, 2014) and many other places, as well as in Ukraine (Katerusha & Matzarakis, 2015).

The mean radiant temperature (T_{mrt}) is one of the most important input meteorological parameters governing human energy balance (Matzarakis et al., 2007; VDI, 1998). The validation results of T_{mrt} have an effect on the accuracy of thermal indexes (including PET) simulated by RayMan. Validation of the accuracy of the mean radiant temperature simulated by the RayMan model was made by Matzarakis et al. (2007, 2010), Thorsson, Lindberg, Eliasson, and Holmer (2007), Andrade and Alcoforado (2008), Krüger, Minella and Matzarakis (2014), Lee and Mayer (2016).

Krüger et al. (2014) compared four different methods for T_{mrt} calculations using the RayMan model. Results showed that all methods overestimate T_{mrt} compared to ISO calculations. But correlations were found to be significant for the first method using input data consisting exclusively of data measured at urban sites. Andrade & Alcoforado (2008) found the linear correlation coefficient between the T_{mrt} estimated with RayMan and that calculated from radiation field measurement for Lisbon was 0.96. The results of Thorson et al. (2007) obtained for the Goteborg, Sweden, showed that the RayMan model works very well during the middle of the day at high sun elevations and underestimates the T_{mrt} at low sun elevations. Matzarakis et al. (2007) provides results of the relationship between T_{mrt} modeled with RayMan and measurements that were carried out in Freiburg, southwest Germany. The results show a relatively good statistical relationship between the T_{mrt} obtained by RayMan and that measured (a correlation coefficient $r^2 = 0.7684$ statistically significant at the 95% level). Lee and Mayer (2016) conducted validation of the mean radiant temperature and physiologically equivalent temperature simulated by RayMan. This validation was based on experimentally determined T_{mrt} and PET values, which were calculated from measured meteorological variables during the daytime under the condition of a clear-sky summer day. Under such conditions T_{mrt} represents the meteorological parameter that mostly defines PET values and thus the accuracy of simulated T_{mrt} is mainly responsible for the accuracy of simulated PET. Generally, the results of validation show that RayMan is capable of simulating T_{mrt} satisfactorily under relatively homogeneous site conditions. However, the inaccuracy of simulated T_{mrt} increases with growing heterogeneity of the simulation site and lower sun elevation. As the aim of this research is to explore human-biometeorological conditions of Kyiv only (and not at certain places with complex structure within the city for some special purpose), for this study we used data obtained at the meteorological station Kyiv at 12.00 UTC. The sun elevation is high at the time for which the PET simulation was made utilizing the RayMan model. Therefore, the accuracy of the obtained results is considered to be at an appropriate level and there is no limitation for using the RayMan model in this research.

For the evaluation of the impact of recent trends in climate on the human thermal comfort during the summer months in Kyiv we have used statistical analysis of the distribution of daily PET values in July calculated for 12.00 UTC for two time periods. The results of study of thermal comfort for the last (modern) time period 1991-2015 were compared with dates from normal climatic period 1961-1990.

Calculations of the statistical distribution of PET values were made with basic module of Software 'Statistica 10'.

Results

The thermal bioclimatic conditions of Kyiv in the period 2005–2014

Daily PET values simulated by RayMan at 12.00 UTC between 2005 and 2014 vary extensively throughout the year (Fig. 2). The lowest value of PET (-30.3°C) occurred in January 2006, the highest 47.0°C in August 2010. Actually, PET values were very high during July and the first half of August 2010, because of a very strong and long-lasting heat wave (Shevchenko, Lee, Snizhko, & Mayer, 2014).

Ranges of PET values are high in some months in Kyiv, for instance, in April and May

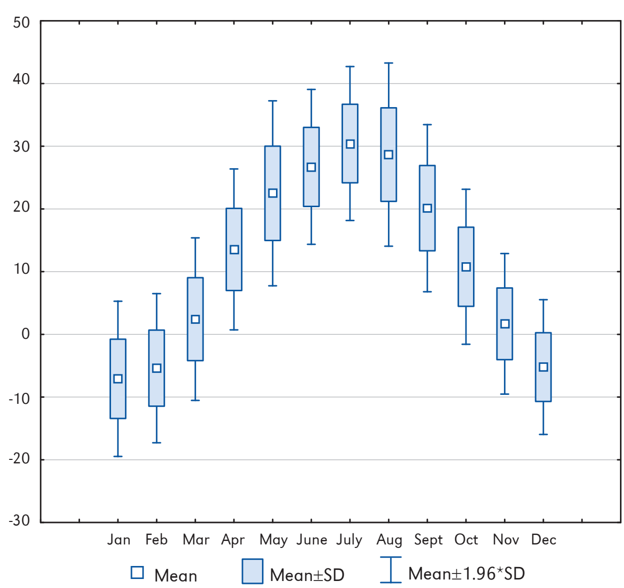

Figure 2. Box-and-Whisker plot of PET values for the period 2005-2014

during the research period the range is nearly 40°C. This is because in these months, in the phase of warm and sometimes even hot weather, invasions of cold air can occur, caused by the inflow of Arctic air masses. This leads to a quick reduction of air temperature and even the production of frosts (Osadchyi et al., 2010). The lowest differentiation in PET values were observed in July – the range was 29°C.

In winter (December, January and February) monthly mean values of PET are below zero, in March and November mean values are approximately zero. The annual average value of PET is 11.7°C.

The analysis of Kyiv's 10-day mean PET values between 2005 and 2014 at 12.00 UTC daily shows that cold stress (nearly always extreme cold stress) can occur from the last 10-day period of November through until the end of February (Fig. 3). In March and November, the probability of cold stress occurrence is also very high, but in the last 10-day period of March and the first 10-day period of November the probability of extreme cold stress is notably reduced and reaches 38 and 42% respectively. The probability of strong, moderate and slight cold stress in this period is rises and reaches 60% in the last 10-day period of March and 57% in the first 10-day period of November. In the months March and November days with thermal comfort are rare but still possible. In April the probability of cold stress is still high (92% – in the first 10-day period, 83% – in the second and 56% – in the third 10-day period), but also prevail days with slight and moderate cold stress. The probability of extreme cold stress varies between 15% (in the first 10-day period of April) and 7% (in the last 10-day period of April). In October the probability of cold stress is still high (84% – in the first 10-day period, 92% – in the second and 74% in the third 10-day period), the occurrence of extreme cold stress varies between 19 and 7% in different 10-day periods. In September the probability of cold stress ranges from 31 to 59% in different 10-day periods (with slight cold stress prevailing). In May it is even less – 46%, 29%, 16%. May cold stress does not cause a problem for Kyiv residents, since this month warm and hot weather mainly prevails in the city.

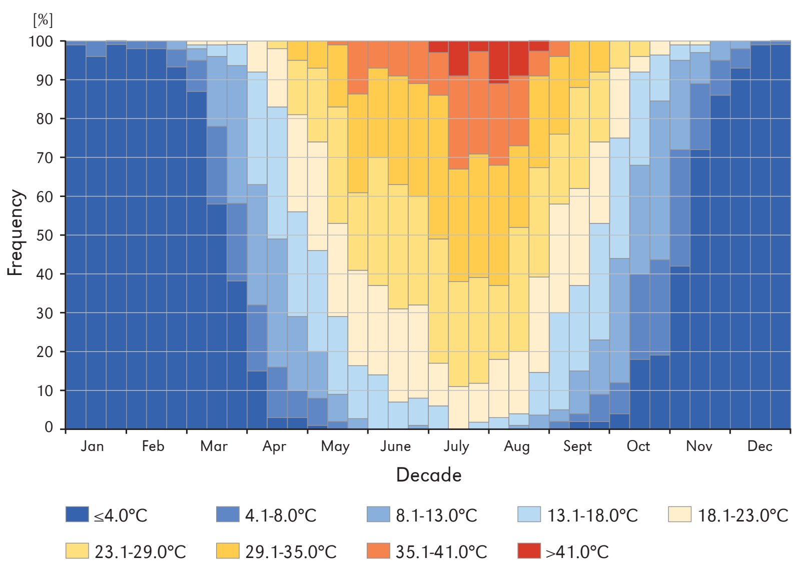

Figure 3. The probability of occurrence of different physiologically equivalent temperature (°C) classes at 12.00 UTC in Kyiv, 2005-2014

The highest probability of thermally comfortable conditions is from the last 10-day period of April to the end of June and from the last 10-day period of August to the end of September. The probability of occurrence of weather with no thermal stress ranges from 21% to 28% in these periods. Heat stress prevails during the summer months. The probability of different heat stress intensities (from slight to extreme) reaches nearly 90% during the second and third 10-day periods of July.

Heat stress affects the health of humans and can lead to marked short-term increases of morbidity and mortality. In the summer months Kyiv residents suffer heat stress now and according to recent climate trends it is very likely the situation will get worse in the future. Therefore, thermal comfort conditions during the summer months and periods of HWs will be discussed more carefully further in this paper. PET values are usually very high during heat wave cases. According to the recommendation of the IPCC, a period of more than 5 consecutive days with daily maximum air temperature ($T_{a,max}$) ≥5°C above the mean daily $T_{a,max}$ for the normal climatic period 1961–1990 defines as a HW (Frich et al., 2002; Radinović & Ćurić, 2012). This definition of heat wave was used as the basis for the determination of HW episodes in Kyiv in the summer months from June to August between 2005 and 2014. The results show that six HW events occurred during the period of research in Kyiv (Tab. 2). Mean $T_{a,max}$ during the HW case was much higher than this parameter for summer months in the normal climatic period 1961-1990 and even much higher than the mean $T_{a,max}$ during the period 1991-2015. Mean maximum air temperature for June in the period 1991-2015 is 23.5°C, for July mean $T_{a,max}$ is 24.5°C and for August mean $T_{a,max}$ is 24.0°C.

The analysis of HWs characteristics showed that the heat wave, which occurred from the end of July till the middle of August 2010, was the longest and strongest in Kyiv. The mean PET values during the period of HW are higher than monthly mean values in the summer months. Daily PET values at 12.00 UTC during the HW are much higher than mean PET values for these days during 2005 and 2014 (Fig. 4). The analysis of PET indicates moderate heat stress nearly each day and slight heat stress in some days from 31 July to 17 August for the period between 2005 and 2014, while during the period of HW PET was higher and reached strong and extreme heat stress.

Changes in human thermal bioclimate of Kyiv during the calendar summer period in 1961-2015

Global climate change has been observed on our planet today as well as in Ukraine.

Table 2. Characteristics of heat wave cases in Kyiv in the summer months June to August between 2005 and 2014

Date	Mean $T_{a,max}$ during the HW case [°C]	Cumulative $T_{a,max}$ during the HW case [°C]	Duration [days]	Mean PET values during the period of HW at 12.00 UTC [°C]
8 June to 14 June 2010	31.6	23.1	7	37.1
14 July to 24 July 2010	33.3	35.1	11	40.5
31 July to 17 August 2010	35.9	108.6	18	42.2
2 July to 9 July 2012	31.1	28.4	8	38.0
25 July to 7 August 2012	33.1	43.7	14	38.0
30 July to 6 August 2014	32.6	18.3	8	37.7

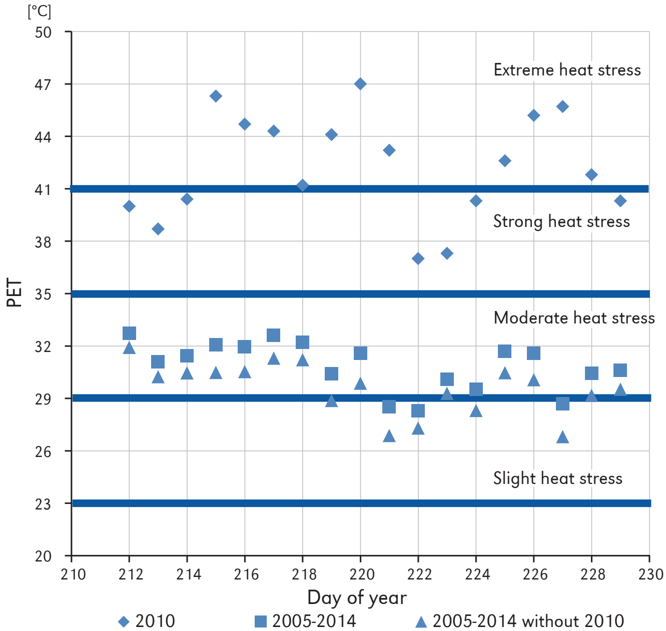

Figure 4. Temporal pattern of PET values at 12.00 UTC during the 18-d heat wave in Kyiv from 31 July (DOY: 212) to 17 August 2010 (DOY: 229) and mean PET values during 2005 and 2014

Studies of the climate of Ukraine indicate that in recent decades the values of some meteorological parameters differ from the long-term average. The most evident of these changes include changes in air temperature and the phenomena associated with it (for example, the frequency of occurrence of hot days, tropical nights (TR20) and heat wave cases, displacement of climatic seasons duration, etc.). In Kyiv over the past 25 years (1991–2015) air temperature increased by 1.2°C compared to the normal climatic period 1961-1990 (defined by WMO) (WMO-TD No. 1377 2007). The air temperature increases (for average, minimum and maximum values) for every month, but the intensity of the increases is different. The increase of the average and maximum air temperature is the most evident in the summer (1.5°C) and minimum air temperature rises are most evident in winter (also 1.5°C) (Tab. 3).

Thus, pronounced increase of air temperature was detected in Kyiv in summer, which expectedly influences thermal comfort and causes changes in bioclimate of the city.

Statistical analysis of the daily PET values distribution in July calculated for the last (modern) time period (1991-2015) and for the normal climatic period (1961-1990) have been used for the evaluation impact of recent trends in climate on the human thermal comfort for the summer period in Kyiv. Generated double period histograms (Fig. 5) show the frequency of occurrence of PET values from different ranges of the variables. The ranges of variables have been installed manually and have step of 5°C.

This made it possible to obtain a detailed description and made comparison of the distribution of real PET values for both compared periods across the full scale of PET values. For the convenience of conducting the analysis, calculations were also made for the main statistical parameters of the PET time series for both periods (Tab. 4).

The median PET value for the modern period (1991-2015) has increased compared to the normal climatic period – from 25.7 to 29.6°C, that is obvious on the basis of air temperature increasing in July as above

Table 3. The anomalies of mean, maximum and minimum air temperature in Kyiv for the 1991-2015 period, compared to 1961-1990

Month, season, year	Mean air temperature [°C]	Maximum air temperature [°C]	Minimum air temperature [°C]
January	2.5	1.9	2.8
February	1.5	1.4	1.4
March	1.6	1.8	1.2
April	1.1	1.0	0.8
May	0.6	0.6	0.2
June	0.9	0.7	0.6
July	2.1	2.1	1.6
August	1.7	1.6	1.2
September	2.0	0.4	0.4
October	0.4	0.3	0.1
November	0.5	0.5	0.4
December	0.2	0.1	0.3
Spring	1.1	1.1	0.7
Summer	1.5	1.5	1.1
Autumn	0.9	0.4	0.3
Winter	1.4	1.1	1.5
Year	1.2	1.0	0.9

mentioned. But despite the general tendency of increasing PET values in July in the last period, some very high PET values were observed in the 1961-1990 period as well. For instance, the highest PET value for the whole period from 1961 to 2015 (46.8°C) was reached in July 1964.

Figure 5 also shows clear displacement of the distribution curve of PET values for the modern period to the right side relative to the graph for the normal climatic period. The difference between the statistical centers of the distribution of PET values of both periods is 3.9°C. The shift of the statistical distribution center (median) to the right along the horizontal scale of PET values has led to significant changes also in several ranges of distribution and grades of physiologically equivalent temperatures. The significance of the changes was examined using classical statistical Student's t-test for two independent and normally distributed series (Wilks 2006). Significant difference between the statistical centers of the distribution of PET values of both periods was confirmed. Null hypothesis about equal of the series for different time period was rejected at the 95% level. On the basis of analysis of the above presented histograms (Fig. 5), a diagram was created to generalize changes of the thermal comfort in Kyiv in the summer periods (Fig. 6).

The analysis of PET indicates the difference between the lowest PET values for both periods is not significant: frequency of days with strong cold stress is 0.2% in the first period and 0.1% in the second period. But the frequency of days with moderate cold stress (8°C > PET ≤ 13°C) has decreased from 2.3% to 0.5%. The frequency of days with slight cold stress (13°C > PET ≤ 18°C) has decreased from 9.7% to 3.1% and days with no thermal stress (18°C > PET ≤ 23°C) from 23% up to 14.7%. The frequency of slightly warm days (23°C > PET ≤ 29°C) with slight heat stress has decreased from 33.7% to 29.7%.

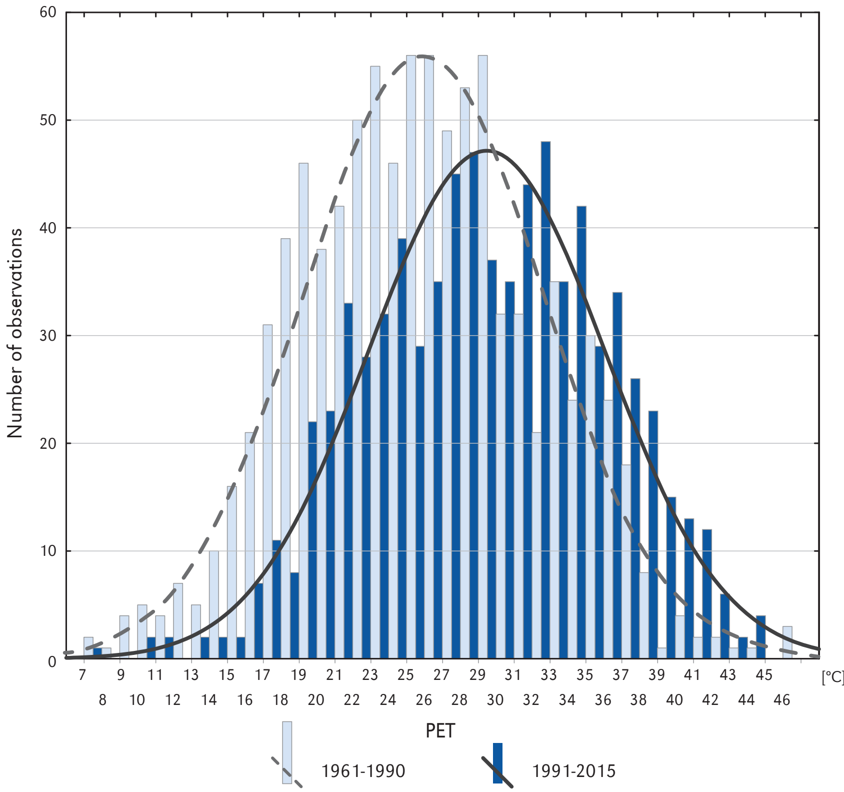

Figure 5. Distribution of daily PET values in July calculated for 12.00 UTC for two climatic periods 1961-1990 and 1991-2015

Table 4. Statistical parameters of daily PET series in July for two climatic periods

Period	Valid N	Median	Min	Max	Standard deviation	Coefficient of variation
1961–1990	930	25.7	7.3	46.8	6.6	25.7
1991–2015	775	29.6	7.9	44.7	6.6	22.3

The reduction of the frequency of comfortable days is associated with an increase in the number of days with heat stress in the climate period 1991-2015. There is an increase of frequency of days with heat stress for all grades of PET above 30°C (Fig. 3).

A detailed consideration of the structure of the distribution of the PET values (Fig. 5, Fig. 6) with respect to the center of the statistical distribution for the last climatic period (29.6°C) shows that frequency of days with temperatures below 29.6°C in the period 1991-2015 decreased and contrariwise, the frequency of days with temperatures above 29.6°C increased in comparison to the period 1961-1990 due to global warming.

The frequency of warm days (29°C > PET ≤ 35°C) with moderate heat stress increased from 21.4% in 1961-1990 to 30.8% in 1991-2015. The increase in the frequency of the days of this PET grade in the modern period is about 10%.

Figure 3 shows a significant accumulation of the number of days in the second period

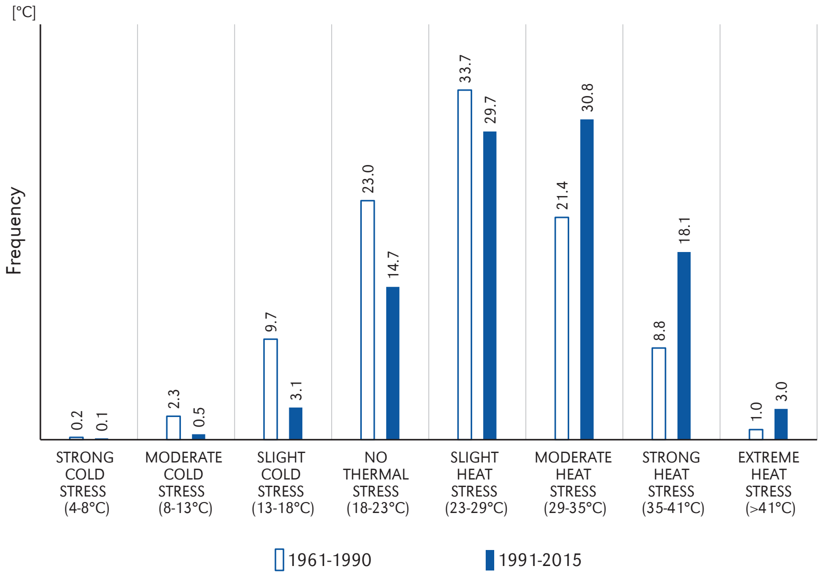

Figure 6. Generalized modern changes in human thermal comfort of Kyiv

in the PET grade of 35-41°C: the frequency of hot days with strong heat stress has increased more than two times from 8.8% to 18.1%. The number of these days in the first period was only 88 (30 years of observations) but in the second period it reached a disproportionately high level of 140 days (25 years of observations).

The comparison of the last PET grade days' frequency of both periods shows that hot and very hot days repeat now 3 times more often than in the normal climatic period (1961-1990).

Thus, the results of the conducted calculations of the statistical distribution of days with different PET values and the comparison of two different time periods have shown significant changes in the climate comfort of the warmest month of the year.

Discussion

The results obtained in this study showed that the annual average value of PET in Kyiv is 11.7°C, in Odesa (a big Ukrainian city on the Black Sea shore) is 11.2°C (Katerusha & Matzarakis, 2015), in Szombathely (Hungary) (Gulyás & Matzarakis, 2009) is 13.7°C. The settlements which are located more to the south and characterized by warmer climate, naturally have noticeably higher mean PET values. For instance, on the island of Hvar (Croatia) the value is 17.3°C (Zaninović & Matzarakis, 2009).

The highest probability of comfortable conditions in Kyiv is from the last 10-day period of April to the end of June and from the last 10-day period of August to the end of September. The probability of occurrence of climatic conditions with no thermal stress ranges within 21–28% in these periods.

Another city of Ukraine, Odessa (Katerusha & Matzarakis, 2015), is located to the south and almost at the same longitude, but on the Black Sea coast. Differences in the duration of the periods with comfortable conditions and conditions with heat stress can be seen when comparing the bioclimatological conditions of Odesa with Kyiv. Duration of the period with comfortable conditions in Kyiv is much longer than in Odessa. In Odesa comfortable conditions occur from the end of April to mid-May and from the end of September to mid-October (five 10-day periods) while in Kyiv this period continues about nine 10-day periods. In Kyiv the probability of heat stress (from slight to extreme) reaches nearly 90% during the second and third 10-day periods of July (only two 10-day periods). Heat stress in Odessa prevails from the last 10 days of June to the end of August (four 10-day periods).

The highest PET values (47.0°C) in Kyiv occurred in August 2010. In Prague (which is situated nearly on the same latitude as Kyiv) maximum PET value is nearly the same – 48.1°C (Zahradníček et al., 2014).

The results of the study showed a pronounced increasing in thermal stress during the heat wave cases. Mean PET values during the period of HWs at 12.00 UTC reached 37.1–42.2°C.

The analysis of the characteristics of HWs showed that the heat wave, which occurred from the end of July till the middle of August 2010, was the longest and strongest in Kyiv – not only between 2005-2014 but also from 1911 (Shevchenko et al., 2014). An extraordinary heat wave was recorded in July and the first half of August in the western part of Russia (Konstantinov et al., 2014).

The blocking anticyclone over the European part of Russia was the reason for the strong heat wave over central and eastern part of Ukraine and western Russia (Dole et al., 2011; Konstantinov et al., 2014; Shevchenko, Samchuk, & Snizhko, 2013). This anticyclone was a high, well-developed baric formation, which was formed during the second 10-day period of July and was observed up to an isobaric surface of 700 hPa. At the level of 500 hPa, a powerful heat ridge corresponded with the anticyclone the axis of which was directed from Asia Minor to the European part of Russia. This position of the center of the anticyclone caused a change in the direction of air flows over Ukraine from the west to the south, southeast, and a little later – to the southwest. The configuration of air flows in combination with a powerful heat source in the Middle East led to advection of heat to the territory of Ukraine and caused the abnormally hot weather (Shevchenko et al., 2013).

The mean PET values for each day from 31 July to 17 August for the period between 2005 and 2014 are graded as moderate heat stress days and with some days – categorized as slight heat stress days, while PET values during the period of HW 2010 are associated with strong and extreme heat stress. Pronounced increase in thermal stress during HW periods was also found by Konstantinov et al. (2014) for Moscow in July 2010, by Matzarakis et al. (2009) for Strasbourg in 2003, by Matzarakis and Nastos (2011b) for Athens for HW cases during long-term period 1955-2001.

Data analysis shows that manifestation of global climate change has been observed in Kyiv during the last few decades. The most pronounced of these changes in air temperature and the phenomena associated with it (for example, the frequency of occurrence of hot days, heat wave cases). During the last 25 years (1990-2015) air temperature in Kyiv increased by 1.2°C when compared with the normal climatic period 1961-1990. The increase in the average and maximum air temperature is the most evident in the summer (1.5°C).

Thus, pronounced increase of air temperature was detected in Kyiv in summer. Air temperature influences human thermal comfort and causes changes in bioclimatic conditions of the city, it is one of the four meteorological parameters used in the estimation of thermal comfort or thermal stress. But air temperature on its own cannot quantify the effect of climate on humans (Matzarakis & Endler, 2010). Studies conducted by Matzarakis (2006), Matzarakis and Amelung (2008) indicated that for climate change conditions the changes based on human thermal comfort indexes (i.e. PET) will be much higher than air temperature changes.

The results of study of thermal comfort for the last time period 1991-2015 were compared with dates from the normal climatic period 1961-1990. The similar methodologies for the research of the recent trends in climate on thermal comfort of humans have been used by other scientists, as well as Matzarakis and Amelung (2008) in global studies and for evaluation of urban/rural thermal comfort changes over the past half-century in Budapest (Hungary) by Németh et al. (2012).

The median PET value for the modern period (1991-2015) has increased significantly from 25.7 to 29.6°C when compare with the normal climatic period.

The difference between non-typical for this climate season low PET values in the same ranges of both periods is not significant: the frequency of days with strong cold stress is 0.2% in the first period and 0.1% in the second period. But the frequency of days with moderate cold stress (8°C > PET ≤ 13°C) has decreased from 2.3 to 0.5%. The frequency of days with slight cold stress (13°C > PET ≤ 18°C) has decreased from 9.7 to 3.1%, comfortable days with no thermal stress (18°C > PET ≤ 23°C) from 23 to 14.7%. The frequency of days with slight heat stress (23°C > PET ≤ 29°C) has decreased from 33.7 to 29.7%.

A reducing of the frequency of comfortable days is associated with an increase in the probability of days with heat stress for the modern climate period (1991-2015). There is an increase of the frequency of days with heat stress for all grades of PET scale above 30°C.

The research of the thermal conditions conducted for Budapest (Hungary) by Kovács and Németh (2012) also has shown the PET averages increase during the period 1981--2010 when compare to the 1961-1990 baseline. The warm stress has become more frequent; however, the cold heat load decreased in Budapest.

A detailed consideration of the structure of the distribution of the PET values with respect to the center of the statistical distribution for the modern climatic period (29.6°C) shows that frequency of days with air temperatures below 29.6°C in the period 1991-2015 decreased and contrariwise, frequency of days with air temperatures above 29.6°C increased in comparison with the period 1961-1990.

The frequency of warm days (29°C > PET ≤ 35°C) with moderate heat stress increased from 21.4% in 1961-1990 up to 30.8% in 1991-2015. The increase in the frequency of the days of this PET grade in the modern period is about 10% and this is very significant.

Obtained results indicated a significant accumulation of the number of days in the second period in the PET grade of 35–41°C: frequency of hot days with strong heat stress has increased more than two times from 8.8 to 18.1%. The number of these days was only 88 in the first period (30 years of observation) but in the second period it reached a disproportionately high level of 140 days (25 years of observation).

Comparison of the last PET grade days' frequency of both periods shows that very hot days repeat now three times more often than in the normal climatic period (1961-1990).

Conclusion

The study analyzed thermal comfort conditions in Kyiv (Ukraine) based on the physiologically equivalent temperature and changes in frequency of heat stress during the summer period due to recent trends in climate.

In Kyiv heat stress prevails during the summer months. The probability of different intensities of heat stress (from slight to extreme) reaches nearly 90% during the second and third 10-day periods of July (the hottest month of the year). Also, PET values are usually very high during heat wave cases. Mean PET values during these periods reached 37.1–42.2°C.

For the evaluation impact of recent trends in climate on human thermal comfort during calendar summer in Kyiv, PET values in July calculated for two time periods (1961--1990 and 1991-2015) were used. As a result of the comparison, it was found that a reduction of the frequency of comfortable days is associated with an increase in the probability of days with heat stress in last time period (1991-2015). The increase in the frequency of the days with moderate heat stress (29°C > PET ≤ 35°C) is about 10% (from 21.4%

in 1961-1990 up to 30.8% in 1991-2015). The frequency of hot days with strong heat stress (PET grade of 35–41°C) has more than doubled from 8.8 up to 18.1%. Comparison of the frequency of days with extreme heat stress in two time periods showed that very hot days repeat now three times more often than in the normal climatic period (1961-1990).

Thus, the results of the conducted calculations of the statistical distribution of days with different PET values and the comparison of two different time periods indicated significant changes in the human thermal comfort of the warmest month of the year.

This is the first study for Kyiv based on thermal indices, which rely on human energy models. The findings obtained in this study can be used for the establishment of the Heat Health Warning System (HHWS) and adaptation plan to climate change, planning of adaptation measures to heat stress, especially during HW cases, and planning business and tourist visits to the capital of Ukraine. This includes Dnipro river cruises, musical festivals, national and international sports competitions and other events in the city.

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Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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