EREM 77/2

Journal of Environmental Research, Engineering and Management
Vol. 77 / No. 2 / 2021
pp. 99–110
DOI 10.5755/10.5755/j01.erem.77.2.23142

Human Thermal Comfort Conditions during Heat Wave Events in Kyiv, Ukraine

Received 2019/04 | Accepted after revision 2021/05

http://dx.doi.org/10.5755/j01.erem.77.2.23142

Human Thermal Comfort Conditions during Heat Wave Events in Kyiv, Ukraine

Olga Shevchenko*

PhD, Associate Professor, Deputy Dean of the Geography Faculty, Taras Shevchenko National University of Kyiv, 01601, 64/13, Volodymyrska Street, City of Kyiv, Ukraine

***Corresponding author:** olga.s.meteo@gmail.com

Assessment of the big cities bioclimate during heat wave (HW) events is a highly topical issue and a focus point for many researchers. Reliable results of the assessment of heat stress (HS) intensity during HWs form the basis for the development and implementation of heat adaptation measures.

In Ukraine, first HW studies started only a few years ago, and the thermal comfort conditions during these atmospheric phenomena have not been explored yet. The purpose of this article is to assess characteristic features of thermal bioclimate in Kyiv during heat wave events. The assessment is based on the thermal index – physiologically equivalent temperature (PET). The RayMan model was used to simulate PET values. As shown in the study, during the period of 1961–2020, 24 heat wave events were observed in Kyiv. Those HWs were characterized by different duration (from 6 to 18 days) and intensity (with the maximum value of cumulative $T_{a,MAX}$ 108.6°C). Thermal comfort conditions registered during heat waves were characterized by heat stress varying from slight (23.7°C) to extreme (47.0°C). To assess the impact of HWs on the human, a classification based on mean PET values during a single heat wave and its duration was proposed. According to this classification, heat waves belong to three following grades: HWs with moderate, strong, and extreme HS. Analysis of HW events in Kyiv for the research period demonstrates four (4) heat waves with moderate heat stress, nineteen (19) with strong stress, and one (1) with extreme stress (specifically, the heat wave in late July–first half of August 2010). The daily PET values at 12 UTC during this HW varied from 37°C to 47°C and were much higher than mean PET values for these days during 2005 and 2014.

Keywords: human thermal comfort conditions, thermal indices, physiologically equivalent temperature, heat stress, heat wave.

Introduction

Heat wave (HW) is an atmospheric phenomenon of a synoptic scale and manifests itself as abnormally hot weather which lasts for a certain period and covers a large area. In the context of global climate change, the frequency of heat wave events is notably growing all over the world, as well as in Ukraine. Summertime heat waves (HWs) top the list of extreme climate and weather events (Gershunov et al., 2009).

The increased use of man-made materials (with low albedo values) and increased anthropogenic heat production leading to changes in urban energy balance are the main causes of an urban heat island. Thus, the urban population is exposed to even stronger heat stress compared with the population in the neighbouring rural areas (Matzarakis et al., 2009). The results of the study show that heat islands in big cities can further exacerbate the negative effect of heat on human health during heat waves. For example, during the well-known HW of 1995 in Chicago, when air temperature reached 38°C, the night temperature was by 2°C higher than in suburban areas because of UHI; in Athens, temperatures in urban areas and suburbs can differ for up to 5°C in the summer; in London, during the HW of August 2003, the heat island intensity reached 8–9°C (Heat and Health: Guidance on Warning-System Development, 2015).

In recent years, the attention of scientists worldwide is being increasingly focused on the heat waves issue (Kyselý, 2010; Gershunov et al., 2009; Shevchenko et al., 2014; Krzyżewska & Dyer, 2018). There are at least several compelling reasons for that. They include growing frequency of manifestation of this phenomenon in the global context over the past decades, negative impact on human health, increased risk of forest fires, reduction in crop yields, and emergence or aggravation of droughts. Although negative implications on population, which can result not only in the deterioration of health, but also in the increased mortality during abnormal heat periods, are usually considered the major reason, thermal comfort conditions during heat waves seem to be less explored to-date in comparison with the frequency, duration and intensity of these phenomena in different regions of the planet. The first research in this field refers to studying the thermal comfort conditions during extreme HW in Athens in July 1987 (Matzarakis & Mayer, 1991). Also, the result of such studies can be found in Matzarakis et al. (2009) for Strasbourg during severe HW of 2003, and in Matzarakis and Nastos (2006) for the heat waves in Athens over the period of 1955–2001. It should be noted that the latest above-mentioned study (Matzarakis & Nastos, 2006) not only analysed the thermal comfort conditions during HWs in Athens, but also identified their events based on the physiological equivalent temperature. The scale and severity of the negative heat impact on human beings was highlighted in the comprehensive publication of 2015 focused on the impact of heat waves on human health, which was prepared by the World Health Organization together with the World Meteorological Organization (Heatwaves and Health: Guidance on Warning-System Development, 2015). Nowadays, there are many successful examples of performing human biometeorological assessments of thermal stress during HW periods utilising thermal indices derived from the human energy balance (Basarin et al., 2016; Konstantinov et al., 2014; Krzyżewska et al., 2020; Roshan et al., 2018; Tomczyk et al., 2020).

Long-term analysis of thermal comfort conditions during heat waves in Kyiv has not been conducted yet. It is largely due to the fact that although the bioclimate studies in Ukraine started a few decades ago (e.g., first research of thermal bioclimatic conditions of Kyiv was conducted in the 1970s–1980s by Eisenschtadt and Sakali (Climate of Kyiv, 2010), but heat waves research was not performed until 2014 (Shevchenko et al., 2014).

The aim of this work is an assessment of the thermal comfort conditions in Kyiv during heat wave events for the period of 1961–2020.

Study area

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

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 calendar summer (June–August) is 19.0°C (Climate of Kyiv, 2010).

Materials and methods

Investigations of human thermal comfort are usually conducted using integral indicators called thermal indices. Growing interest in the problem of the impact of meteorological parameters on the human body has resulted in the emergence of numerous thermal indices based on various approaches to assessment of the factors that determine human thermal comfort conditions. The first thermal indices were developed about 100 years ago. Such indices were very simple and only meteorological parameters were used as input information for the calculations. Nowadays, more complex indices, which are based on human energy balance, are used for investigations. Physiologically equivalent temperature (Mayer & Höppe, 1987; Höppe, 1999; Matzarakis et al., 1999) belongs to these indices. PET is a thermal index derived from the human energy balance. The basis for PET calculation is "The Munich energy balance model for individuals" (MEMI) (Höppe, 1999). Compared with other thermal indices which are also based on the human energy balance, PET has the advantage of a widely known unit (degrees Celsius), which makes results more comprehensible to people who are not so familiar with human-biometeorological terminology (Matzarakis et al., 1999). A comprehensive review of approaches and methods of the outdoor human thermal perception conducted by Potchter et al. (2018) has shown that PET belongs to four widely used human thermal indices out of the165 that have been developed. 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 (Potchter et al., 2018). Thus, PET has one more advantage, that there are analysis and results available for many cities worldwide, and it is easy to compare thermal bioclimatic conditions in different parts of the world.

To estimate thermal comfort conditions, PET values were divided into nine physiological stress grades (Table 1).

The calculation of PET is performed utilizing the RayMan model (Matzarakis and Rutz, 2006).

For PET simulation, the following data groups are used in the RayMan model:

I. Date and time.

II. Geographic data: location name, geographic longitude and latitude, elevation above sea level (altitude), and time zone.

III. Meteorological data: air temperature (°C), vapour pressure (hPa) or relative humidity (%), wind speed (m/s) and cloud cover (octas).

Table 1. *Ranges of the physiological equivalent temperature for different grades of thermal perception by human beings and physiological stress on human beings (Matzarakis et al., 2009)*

PET	Thermal perception	Grade of physiological stress
< 4.0°C	very cold	extreme cold stress
4.1–8.0°C	cold	strong cold stress
8.1–13.0°C	cool	moderate cold stress
13.1–18.0°C	slightly cool	slight cold stress
18.1–23.0°C	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
> 41.0°C	very hot	extreme heat stress

Global radiation can be specified as a fixed input parameter or it can be calculated from time, date, geographic position and a cloud cover. From these parameters, an initial global radiation is calculated, that is later corrected by sky view factor and shading.

In this study, daily data obtained from the weather station "Kyiv" of the Ukrainian Hydrometeorological Centre taken at 12.00 UTC for the period June 1–August 31, 1961–2020, were used.

IV. Personal human data and parameters that may affect heat perception (height, weight, age, sex, clothing, activity, and position).

In this research, the simulations referred to standard parameters of a person: 35-year-old man, 1.75 m height, 75 kg weight, wearing clothing with a heat resistance of 0.9 CLO, sedentary, with heat producing is equivalent to 80 W.

So far, there is no objective and uniform HW definition that would be used as a criterion to identify this atmospheric phenomenon in all studies, without exception (Gershunov et al., 2009; Monteiro et al., 2013). Shevchenko et al. (2014) substantiated that the definition of heat waves recommended by the Intergovernmental Panel on Climate Change (IPCC) is suitable for the investigations of HW climatology on the territory of Ukraine. According to the IPCC definition, a HW is a period of more than 5 consecutive days with daily $T_{a,max} \geq$ 5°C above the mean daily $T_{a,max}$ for the normal climatic period 1961–1990 (Radinović & Ćurić, 2012). This definition of heat wave was used as the basis for the determination of HW episodes in Kyiv.

Time series of daily maximum air temperature in the summer months of June to August 1961 to 2020 was used for determining heat wave events in Kyiv.

Results and discussion

As a result of air temperature series analysis, it was found that over the period of 1961–2020 in Kyiv there were 24 heat wave events (Table 2). Despite a small number of HW events during the investigation period, this phenomenon was observed every decade (once per ten years). The results show that the greatest number of HW events occurred in the decade of 2011–2020 (Fig. 1). However, it should be noted that the highest number of HW events was found during the decadal periods after 1990. In Kyiv over the past 30 years (1991–2020), the number of HWs increased more than twice (from 7 to 17 events) compared with the normal climatic period

Fig. 1. *Number of HWs and their total duration (in days) in Kyiv for the period 1961–2020*

Table 2. *Characteristics of heat wave events in Kyiv in the summer months over the period 1961–2020*

Date	HW duration (days)	Cumulative $T_{a,MAX}$ (°C)	Mean maximum air temperature during the HW event (°C)
25.07–31.07.1963	7	10.7	31.2
03.08–10.08.1963	8	16.1	32.6
16.06–24.06.1964	9	18.8	30.6
15.06–21.06.1968	7	10.8	29.7
15.07–29.07.1972	15	24.1	31.4
16.06–23.06.1975	8	19.3	30.8
26.08–31.08.1985	6	9.8	28.9
07.06–20.06.1999	14	32.6	30.6
17.08–23.08.2000	7	26.1	32.2
20.07–28.07.2001	9	25.4	32.5
08.07–22.07.2002	15	28.1	31.5
08.06–14.06.2010	7	23.1	31.7
14.07–24.07.2010	11	35.1	33.1
31.07–17.08.2010	18	108.6	36.0
02.07–09.07.2012	8	28.4	32.4
25.07–07.08.2012	14	43.7	30.0
30.07–06.08.2014	8	18.3	32.6
04.07–09.07.2015	6	16.0	31.6
24.08–29.08.2015	6	13.2	29.4
31.07–05.08.2017	6	15.8	32.9
16.08–21.08.2017	6	27.1	33.1
10.06–17.06.2019	8	28.2	31.3
19.06–24.06.2019	6	15.9	31.6
07.06–13.06.2020	7	20.2	31.5

1961–1990. The total duration of HW events for different periods also varied significantly – from 6 days during the period 1981–1990 to 75 days in 2011–2020.

The average duration of HW in Kyiv during the investigation period was 9 days, fluctuating within the range from 6 to 18 days. It should be noted that since there are a number of different definitions of this phenomenon, according to which an episode exceeding three days (provided that other criteria are met) can also be recognized as HW (Ding et al., 2010; Kyselý, 2010), and the fact of the negative effect of heat on the human body, even events of a 6-day duration should not be considered short and need further analysis, because those hot periods could result in a significant deterioration of thermal comfort conditions and have an adverse effect on human health. Also, it is worth mentioning that in Kyiv between 1961 and 2020, only six events of HW were 6-day long, while between 1911 and 1960 there were found nine such cases (Shevchenko, 2013).

To characterize the intensity of HW, a cumulative $T_{a,MAX}$ for a single HW is usually used. Kyselý (2002) found that it was most appropriate for this purpose. Typically, cumulative $T_{a,MAX}$ for a single HW is calculated as the sum of the temperature differences between the maximum daily air temperature and a threshold value, which depends on the applicable heat wave definition. The calculation of the cumulative $T_{a,MAX}$ excess started at the first day of a period, which was subsequently identified as a HW. According to the definition used in this study, the $T_{a,MAX}$ excess is the difference between the daily $T_{a,MAX}$ and the mean daily $T_{a,MAX}$ in the standard period 1961–1990 increased by 5°C. According to the values obtained of the cumulative $T_{a,MAX}$, the intensity of different HW events in Kyiv was distinctly variable. The highest cumulative $T_{a,MAX}$ for the investigation period was recorded in 2010 and amounted to 108.6°C (Table 2).

Using the research vocabulary of biometeorology, a heat wave can be defined as a period with a constant heat load or excessively hot weather, resulting in at least one of the following health implications – deterioration of health and increased mortality or the number of ambulance calls (Kovats & Jendritzky, 2006). However, it is obvious that despite a quite accurate reflection of the heat waves concept from the biometeorology point of view, this definition does not contain any measurable numerical criteria, which makes its application for scientific research totally unsuitable.

To quantify the duration of HW events and their impact on the human, Matzarakis and Nastos (2006) used consecutive days (three and more) and chose thresholds for PET values and daily minimum air temperature ($T_{a,MIN}$). The thresholds for physiologically equivalent temperature was ≥ 35°C and for T_{aMIN} ≥ 23°C. It is worth noting that PET values within the range of 35.1–41.0°C correspond to strong heat stress, and above 41.0°C to extreme heat stress. Analysis of average monthly air temperatures in Athens and Kyiv during the summer months (Table 3) reveals a significant difference, namely: in June the air temperature in Athens is higher than in Kyiv by 6.4°C, in July by 7.7°C, and in August by 8.0°C. Given much hotter climate conditions in Athens and a certain correlation between adaptation to a specific climate and heat perception of a human body, it becomes apparent that periods with significantly lower (compared with Athens) PET values can lead to a thermal stress in population of Kyiv and, accordingly, the PET threshold values used earlier by Matzarakis and Nastos for HW identification are not applicable in Kyiv.

Table 3. *Mean monthly air temperature (°C) in Athens and Kyiv during the normal climatic period (1961–1990) (calculated from the data of Sakellariou et al., 2000, Climate Cadastre of Ukraine, 2006))*

Cities/Months	June	July	August
Athens	24.6	27.0	26.6
Kyiv	18.2	19.3	18.6

Additionally, if a value of certain thermal indices was used for identification of HW events, such predetermination, in fact, imposes certain bioclimatic pre-conditions (moderate, strong or extreme heat stress) on the heat wave periods, instead of studying bioclimate over the periods that were identified as HW according to certain meteorological criteria. Therefore, in order to achieve the objectives of this study, we simulated and analysed PET values at 12.00 UTC every day for 24 HW events that meet the IPCC criteria for this atmospheric phenomenon.

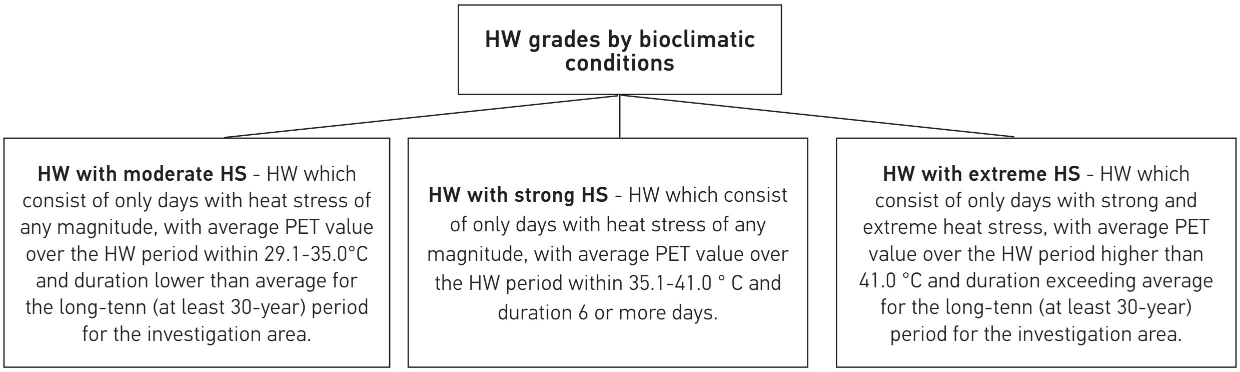
The analysis of the thermal comfort conditions at 12.00 UTC during the heat waves in Kyiv since 1961 shows that conditions varying from slight to extreme heat stress were observed during these periods (Table 4). No days with comfort conditions and only 8 days with slight heat stress out of 216 days (total duration of all HWs for the investigation period in Kyiv), or 3.7%, have been recorded during these periods. The days with slight heat stress were recorded mainly at the beginning or at the end of the heat wave episode, and they are predominantly associated with cloud cover which significantly reduces the direct solar irradiation of the human body, lowers the mean radiant temperature and, therefore, reduces the PET values. 38 days were characterized with extreme heat stress (17.6%), and 117 days with strong heat stress (54.2% of the total).

Table 4. *Thermal conditions during heat wave events in Kyiv in the summer months over the period 1961–2020*

Date and duration (days)	Mean PET values at 12.00 UTC during the HW period (°C)	Range of PET values (°C) at 12.00 UTC during the HW
25.07–31.07.1963 (7)	37.8	34.8 (moderate HS) – 42.0 (extreme HS)
03.08–10.08.1963 (8)	40.8	36.7(strong HS) – 43.5 (extreme HS)
16.06–24.06.1964 (9)	37.2	31.6 (moderate HS) – 42.4 (extreme HS)
15.06–21.06.1968 (7)	32.0	27.9 (slight HS) – 39.1 (strong HS)
15.07–29.07.1972 (15)	36.4	31.7 (moderate HS) – 46.2 (extreme HS)
16.06–23.06.1975 (8)	34.1	27.3 (slight HS) – 39.3 (strong HS)
26.08–31.08.1985 (6)	29.8	26.5 (slight HS) – 31.9 (moderate HS)
07.06–20.06.1999 (14)	35.2	28.6 (slight HS) – 41.7 (extreme HS)
17.08–23.08.2000 (7)	36.0	23.7 (slight HS) – 43.5 (extreme HS)
20.07–28.07.2001 (9)	38.8	34.5 (moderate HS) – 42.7 (extreme HS)
08.07–22.07.2002 (15)	37.1	34.1 (moderate HS) – 39.6 (strong HS)
08.06–14.06.2010 (7)	37.1	33.2 (moderate HS) – 40.0 (strong HS)
14.07–24.07.2010 (11)	40.5	36.6 (strong HS) – 44.1 (extreme HS)
31.07–17.08.2010 (18)	42.2	37.0 (strong HS) – 47.0 (extreme HS)
02.07–09.07.2012 (8)	38.0	33.4 (moderate HS) – 42.3 (extreme HS)
25.07–07.08.2012 (14)	38.0	29.9 (moderate HS) – 43.8 (extreme HS)
30.07–06.08.2014 (8)	37.7	34.7 (moderate HS) – 42.0 (extreme HS)
04.07–09.07.2015 (6)	35.8	32.9 (moderate HS) – 38.3 (strong HS)
24.08–29.08.2015 (6)	32.7	29.0 (slight HS) – 37.6 (strong HS)
31.07–05.08.2017 (6)	38.4	34.6 (moderate HS) – 40.9 (strong HS)
16.08–21.08.2017 (6)	38.5	34.9 (moderate HS) – 41.4 (extreme HS)
10.06–17.06.2019 (8)	36.8	34.5 (moderate HS) – 39.7 (strong HS)
19.06–24.06.2019 (6)	36.6	33.1 (moderate HS) – 41.4 (extreme HS)
07.06–13.06.2020 (7)	35.9	34.1 (moderate HS) – 38.2 (strong HS)

Although the population of Kyiv has been suffering from heat stress during the heat waves, thermal load and duration of HW episodes were somewhat different in each single case and, obviously, the health impact also varied. As mentioned previously, to characterize the HW intensity, a cumulative $T_{a,MAX}$ is usually used. Also, quite often this parameter serves as a determinant for classification of HWs by intensity (for example, to identify the mega heat waves (MHWs)). Krzyżewska and Dyer (2018) defined MHW as a period during which the maximum daily air temperature for more than 6 consecutive days exceeds 30°C (including one day with the temperature below this value), and cumulative $T_{a,MAX}$ – 30°C. According to the above criteria, over the period of 1961–2020, only three episodes in Kyiv can be identified as MHW, namely: heat wave from July 20 to July 28, 2001; from July 31 to August 17, 2010; and from July 25 to August 7, 2012. All other events just fall into the "regular heat wave" grade. However, if we look at Table 4 in more detail, it becomes apparent that all identified HW events vary significantly

Fig. 2. *Types of heat waves according to the grade of human heat stress*



in terms of their impact on the human body, and a logical solution would be to split them into more than two groups based on the degree of such impact. Therefore, for a more objective assessment of the HW's impact on the human, it is proposed to introduce their classification based on the mean values of physiological equivalent temperature and HW duration. The results of numerous studies demonstrate that the long-lasting HW causes a significantly adverse impact on health, especially in vulnerable population groups. For example, mortality increases 1–1.5 times compared with the cases of short-term HW (D'Ippoliti et al., 2010; Montero et al., 2012; Rocklov et al., 2012).

The proposed classification includes three grades: HWs with moderate heat stress, HWs with strong heat stress, and HWs with extreme heat stress (Fig. 2).

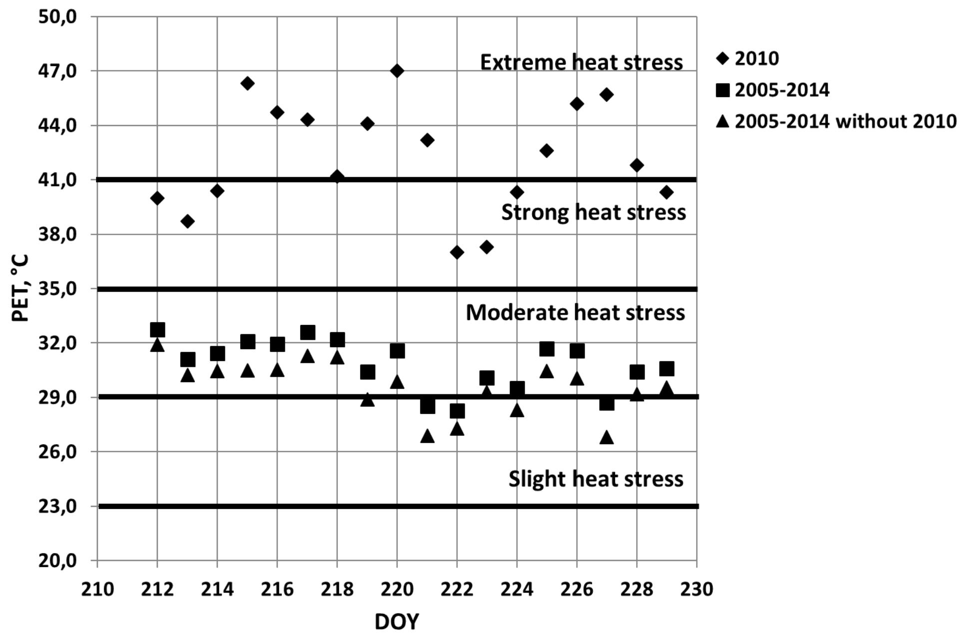
The analysis of the HW events in Kyiv over the period of 1961–2020 shows that during this period one heat wave with extreme heat stress and four heat waves with moderate heat stress were recorded in the city, and all other events were classified as HWs with strong heat stress (Table 5).

The heat wave of late July–August 2010 was outstanding, not only in terms of an extreme heat stress, but also due to the highest duration and intensity for Kyiv since 1911 (Shevchenko et al., 2014). It began on July 31 and lasted until August 17. Over its duration, the average daily air temperature exceeded the normal by 7–11°C. The maximum air temperature was recorded on August 8 and reached 39.2°C. The air temperature at night time was 21–24°C, and in the daytime it was 36–39°C. On August 3–9 and 12–15, absolute (historical)

Table 5. *Classification of heat waves which were observed in Kyiv during the period 1961–2020 according to the grade of human thermal stress*

HWs with moderate HS	HWs with strong HS	HWs with extreme HS
	25.07–31.07.1963	
	03.08–10.08.1963	
	16.06–24.06.1964	
15.06–21.06.1968		
	15.07–29.07.1972	
16.06–23.06.1975		
26.08–31.08.1985		
	07.06–20.06.1999	
	17.08–23.08.2000	
	20.07–28.07.2001	
	08.07–22.07.2002	
	08.06–14.06.2010	
	14.07–24.07.2010	
		31.07–17.08.2010
	02.07–09.07.2012	
	25.07–07.08.2012	
	30.07–06.08.2014	
	04.07–09.07.2015	
24.08–29.08.2015		
	31.07–05.08.2017	
	16.08–21.08.2017	
	10.06–17.06.2019	
	19.06–24.06.2019	
	07.06–13.06.2020	

Fig. 3. *Temporal pattern of PET values at 12.00 UTC during the 18-day heat wave in Kyiv from 31 July (DOY: 212) to 17 August 2010 (DOY: 229) and mean PET values during 2005 and 2014*



values of maximum air temperatures for these days were exceeded by 0.2–5.2°C.

The daily PET values at 12.00 UTC during this HW varied from 37°C to 47°C and belong to the grade of strong and extreme heat stress. They were much higher than mean PET values for these days during 2005 and 2014 (Fig. 3). The maximum physiological equivalent temperature during the period of this HW (47.0°C) was recorded on the same day as the maximum air temperature, namely on August 8. The mean PET values for the period of 2005–2014 were within the range of 28.3–32.7°C and belong to the grade of moderate and slight heat stress.

A particularly extreme heat wave occurred in July and August 2010 not only in Ukraine but also Western Russia (Barriopedro et al., 2011; Grumm, 2011; Rahmstorf & Coumou, 2011). Due to its dimension in terms of amplitude and spatial extent, it was evaluated as a mega HW event by Barriopedro et al. (2011). The summer temperatures in Europe in 2010 were on average by 0.2°C higher than in 2003. The area exposed by the extreme heat was more than two million square kilometres, and very high temperatures lasted between 15- and 61-day averages (Basarin et al., 2020). 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 (Konstantinov et al., 2014; Shevchenko et al., 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 centre 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., 2014).

Conclusions

During the period of 1961–2020, 24 heat wave events occurred in Kyiv. Those HWs were characterized by different duration (6 to 18 days) and intensity (with the maximum value of cumulative $T_{a,MAX}$ 108.6°C). Assessment of thermal comfort conditions in Kyiv during the heat waves, based on physiologically equivalent temperature, has shown that HW events are characterized by heat stress varying from slight (23.7°C) to extreme (47.0°C). To assess the impact of HWs on the human body, the classification based on mean PET values during a single heat wave and its duration was proposed. According to the classification, heat waves are divided into the following three grades: HWs with moderate heat stress, HWs with strong heat stress, and HWs with extreme heat stress. Analysis of HW events in Kyiv for the research period demonstrates that there were four (4) heat waves with moderate heat stress, nineteen (19) with strong stress, and one with extreme stress (namely, the heat wave in late July–first half of August 2010). The daily PET values at 12 UTC during this HW varied from 37°C to 47°C and were much higher than mean PET values for these days during 2005 and 2014.

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 and planning business and tourist visits to Kyiv during the summer months.

References

Barriopedro D., Fischer E.M., Luterbacher J., Trigo R.M., García-Herrera, R. (2011) The hot summer of 2010: redrawing the temperature record map of Europe. Science (New York, N.Y.), 332(6026): 220-224. https://doi.org/10.1126/science.1201224

Basarin B., Lukić T., Matzarakis A. (2016) Quantification and assessment of heat and cold waves in Novi Sad, Northern Serbia. International Journal of Biometeorology. 60(1): 139-150. https://doi.org/10.1007/s00484-015-1012-z

Climate Cadastre of Ukraine (2006). [CD-ROM].

Ding T., Qian W. and Yan Z. (2010) Changes in hot days and heat waves in China during 1961-2007. International Journal of Climatology 30: 1452-1462. https://doi.org/10.1002/joc.1989

D'Ippoliti D., Michelozzi P., Marino C., de'Donato F., Menne B., Katsouyanni K., Kirchmayer U., Analitis A., Medina-Ramon M., Paldy A., Atkinson R., Kovats S., Bisanti L., Schneider A., Lefranc A., Iniguez C., Perucci C.A. (2010) The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. Environmental Health 9(37). https://doi.org/10.1186/1476-069X-9-37

Gershunov A, Cayan D.R., Iacobellis S.F. (2009) The great 2006 heat wave over California and Nevada: signal of an increasing trend. Journal of Climate. 22: 6181-6203. https://doi.org/10.1175/2009JCLI2465.1

Grumm R.H. (2011) The central European and Russian heat event of July-August 2010. Bulletin of the American Meteorological Society. 92(10): 1285-1296. https://doi.org/10.1175/2011BAMS3174.1

Heatwaves and Health: Guidance on Warning-System Development. (2015). - WMO-No. 1142.

Höppe P. (1999) The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment. International Journal of Biometeorology. 43: 71-75. https://doi.org/10.1007/s004840050118

Konstantinov P.I., Varentsov M.I., Malinina E.P. (2014) Modeling of thermal comfort conditions inside the urban boundary layer during Moscow's 2010 summer heat wave (case-study). Urban Climate. 10(P3): 563-572. https://doi.org/10.1016/j.uclim.2014.05.002

Krzyżewska A., Dyer J. (2018) The August 2015 mega-heatwave in Poland in the context of past events. Weather. 73 (7): 207-214. https://doi.org/10.1002/wea.3244

Krzyżewska A., Wereski S., Demczuk P. (2020) Biometeorological conditions during an extreme heatwave event in Poland in August 2015. Weather. 75(6): 183-189. https://doi.org/10.1002/wea.3497

Kovats R.S., Jendritzky G. (2006) Heat-waves and human health. In: Menne, B., Ebi, K.L. (eds.) Climate Change and Adaptation Strategies for Human Health. WHO, Springer.

Kovats R.S., Hajat S. (2008) Heat stress and public health: a critical review. Annual Review of Public Health. 29: 41-55. https://doi.org/10.1146/annurev.publhealth.29.020907.090843

Kyselý J. (2010) Recent severe heat waves in central Europe: how to view them in a long-term prospect? International Journal of Climatology 30: 89-109. https://doi.org/10.1002/joc.1874

Kyselý J. (2002) Temporal fluctuations in heat waves at Prague-Klementinum, the Czech Republic, from 1901-97, and their relationships to atmospheric circulation. International Journal of Climatology 22: 33-50. https://doi.org/10.1002/joc.720

Matzarakis A., De Rocco M.,Najjar G. (2009) Thermal bioclimate in Strasbourg – the 2003 heat wave. Theoretical Applied Climatology. 98: 209-220. https://doi.org/10.1007/s00704-009-0102-4

Matzarakis A., Mayer H. (1991) The extreme heat wave in Athens in July 1987 from the point of view of human biometeorology. Atmospheric Environment. 25 (2): 203-211. https://doi.org/10.1016/0957-1272(91)90055-J

Matzarakis A., Nastos P. (2006) Heat waves in Athens. In: Proceedings of the 8th Conference on Meteorology-Climatology-Atmospheric Physics (COMECAP 2006), Athens, Greece, 24-26 May 2006, pp 153-160.

Matzarakis A., Mayer H. and Iziomon M.G. (1999) Applications of a universal thermal index: physiological equivalent temperature. International Journal of Biometeorology. 43: 76-84. https://doi.org/10.1007/s004840050119

Matzarakis A., Rutz F. (2006) RayMan: A Tool for Research and Education in Applied Climatology. In: Proceedings of the 8th Conference on Meteorology-Climatology-Atmospheric Physics (COMECAP 2006), Athens, Greece, 24-26May 2006, pp. 161-168.

Mayer H., Hoppe P. (1987) Thermal comfort of man in different urban environments. Theoretical and Applied Climatology. 38(1): 43-49. https://doi.org/10.1007/BF00866252

Monteiro A., Carvalho V., Oliveira T., Sousa C. (2013) Excess mortality and morbidity during the July 2006 heat wave in Porto, Portugal. International Journal of Biometeorology. 57: 155-167. https://doi.org/10.1007/s00484-012-0543-9

Osadchyi V., Kosovets O. and Babichenko V (Eds.) (2010) The climate of Kyiv (320 p.) Kyiv: Nika-Tsentr.

Potchter O., Cohen P., Lin T.P., Matzarakis A. (2018) Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification. Science of the Total Environment. 631-632: 390-406. https://doi.org/10.1016/j.scitotenv.2018.02.276

Radinović D., Ćurić M. (2012) Criteria for heat and cold wave duration indexes. Theoretical and Applied Climatology. 107: 505-510. https://doi.org/10.1007/s00704-011-0495-8

Rahmstorf S., Coumou D. (2011) Increase of extreme events in a warming world. Proceedings of the National Academy of Sciences of the United States of America. 108(44): 17905-17909. https://doi.org/10.1073/pnas.1101766108

Rocklov J., Barnett A.G., Woodward A. (2012) On the estimation of heat-intensity and heat-duration effects in time series models of temperature-related mortality in Stockholm, Sweden. Environtal Health. 11(1): 23. https://doi.org/10.1186/1476-069X-11-23

Roshana G.R., Ghanghermeha A.A., Kong Q. (2018) Spatial and temporal analysis of outdoor human thermal comfort during heat and cold waves in Iran. Weather and Climate Extremes. 19: 58-67. https://doi.org/10.1016/j.wace.2018.01.005

Sakellariou N.K., Kambezidis H.D., Gouvas M.A. (2000) Mean monthly air temperatures in Athens, Greece. Theoretical and Applied Climatology. 67: 201-203. https://doi.org/10.1007/s007040070009

Shevchenko O., Lee H., Snizhko S., Mayer H. (2014) Long-term analysis of heat waves in Ukraine. International Journal of Climatology 34 (5): 1642-1650. https://doi.org/10.1002/joc.3792

Shevchenko O.G. (2013) The research of heat waves of summer period, which observed in Kiev during 1911-2010. Ukrainian Hydrometeorological Journal. 12: 142-150. (in Ukrainian)

Shevchenko O.G., Samchuk E.V., Snizhko S.I. (2013) Characteristics of synoptic processes during heat wave in July-August 2010 in Ukraine. Proceedings of the Russian State Hydrometeorological University. 29: 85-94. (in Russian)

Tomczyk A.M., Bednorz E., Matzarakis A. (2020) Human-biometeorological conditions during heat waves in Poland. International Journal of Climatology. 40(12): 5043-5055. https://doi.org/10.1002/joc.6503

This article is an Open Access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 (CC BY 4.0) License (http://creativecommons.org/licenses/by/4.0/).