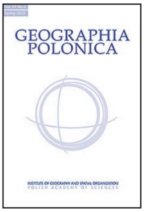

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LONG-TERM ANALYSIS OF THERMAL COMFORT CONDITIONS DURING HEAT WAVES IN UKRAINE

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Abstract

The aim of this study is assessment of thermal comfort conditions during heat waves in Ukraine in the years 1961-2015. The assessment is based on the thermal index Physiologically Equivalent Temperature. This study uses data from 29 meteorological stations across Ukraine. The research showed an increasing frequency of occurrence of heat waves (HWs) in the territory of Ukraine in the last decades. East and south Ukraine (except of coastal stations) experienced the most strenuous human-biometeorological conditions whilst HWs were recorded in the country. Lower mean PET values were found in Western region of the country. The obtained results suggest that the HW event of 2010 was the longest and the most strenuous HW in human-biometeorological terms since 1961.

Key words

heat waves • human thermal comfort conditions • heat stress • physiologically equivalent temperature • Ukraine

Introduction

Summertime HW events top the list of extreme climate and weather events (Gershunov et al., 2009). Extreme heat waves were observed in Central Europe in June and August 2003 (Fink et al., 2004), in June and July 2006 (Fouillet et al., 2008; Rebetez et al., 2009), in summer 2015 (Hoy et al., 2017; Krzyżewska & Dyer, 2018); as well as in Eastern Europe and Western Russia in July and August 2010 (Grumm, 2011; Shevchenko et al., 2020). Heat waves cause heat stress and have significant impacts on the wellbeing, efficiency and health of humans, and can lead to marked short-term increases in morbidity and mortality (Basu, 2009; Gosling et al., 2009). For instance, more than 100,000 people died during the most intense heat waves of 2003 over Western Europe and 2010 over Western Russia (Basarin et al., 2020). Results of climate simulations project more intense, more frequent and longer lasting heat waves in the 21st century (Ballester et al., 2010; Heinrich & Gobiet, 2012;). This could lead to a significant increasing in the heat-related mortality rate in the summer (Laschewski & Jendritzky, 2002; Smith et al., 2014). Thus, global warming is expected to gradually alter the seasonal mortality cycle. Ballester, Robine, Herrmann and Rodó (2011) assessed that in Europe, the rise in heat-related mortality would start to compensate for the reduction of deaths from cold during the second half of this century.

Sensitivity to heat stress varies according to many aspects, such as age, health, lifestyle, poverty levels, infrastructure and buildings, access to health care, and social structures (Ruuhela et al., 2017). People with respiratory and cardiovascular diseases, diabetes, or chronic mental illnesses, patients taking specific drugs or medications that affect perception or regulation of heat in the body, young children and older people, whose capacity to adapt may no longer be sufficient, are found to be particularly vulnerable to temperature extremes (Kovats & Hajat, 2008; Hajat et al., 2010; Bunker et al., 2016). The elderly are most vulnerable to heat stress. For instance, the 2003 HW in Europe caused an estimated 15,000 excess deaths in France, of which 70% were in the age range of 75-94 (Le Tertre et al., 2006; Thorsson et al., 2014).

Evaluation of human thermal comfort during HW events only in terms of air temperature, or a combination of different meteorological variables, can lead to an underestimation of the heat stress intensity and negative impact of this atmospheric phenomenon on people. Parsons (2014) emphasized that six parameters for thermal stress estimation (air temperature, humidity, air velocity, heat radiation, and two individual factors – metabolic rate and the effect of clothing) must be taken into account. Thus consideration of human biometeorology is required to be appraised in association with the human thermal environment when human thermoregulation is to be assessed. Therefore, thermoregulatory models are required and biometeorological indices based on those models are important for estimating the human thermal environment and stress (Basarin et al., 2020). Staiger et al. (2019) suggested the use of the Universal Thermal Climate Index (UTCI), Perceived Temperature (PT), Physiologically Equivalent Temperature (PET), and Effective Temperature (ET) to examine the impacts of extreme heatwaves on human health. There are many successful examples of making human biometeorological assessments of thermal stress during HW periods utilizing thermal indices derived from the human energy balance (Matzarakis et al., 2009; Matzarakis & Nastos, 2011; Konstantinov et al., 2014; Basarin et al., 2016; Roshan et al., 2018; Krzyżewska et al., 2020; Tomczyk et al., 2020).

A research of heat waves for Ukraine has not been performed up to 2014 and first investigation has been devoted the spatiotemporal variability of HWs just for 13 selected stations (Shevchenko et al., 2014). Research into the bioclimatic conditions of Ukraine has largely been conducted based on very simple indices which rely on only a few meteorological parameters for their calculation. Obviously, these indices are very simple to calculate, but the obtained results cannot fully represent real thermal stress on humans. Indices based on the human energy balance (such as PET and UTCI) were used just in a few researches of bioclimatic conditions – for Odesa by Katerusha and Matzarakis (2015), for Kyiv by Shevchenko et al. (2020) and for the Carpathian mountains by Błażejczyk et al. (2020). Therefore, the aim of this study is to get a deeper insight into the characteristics of heat waves in Ukraine (including the temporal and spatial distribution of HW events). In addition, the authors aim to articulate the human-biometeorological conditions during HW events in Ukraine during the years 1961-2015 and make a designation of the most human-biometeorologically onerous HW events.

The research was conducted in two steps. First, HW events were identified for the period 1961-2015 and the basic characteristics of these episodes (i.e. number, intensity, duration) were calculated. Then, human-biometeorological conditions during the designated HW events was analyzed.

Research area, data and methods

The territory of Ukraine is located between 52°20´ and 44°23´N as well as 22°5´ and 41°15´E. On the south, the territory of Ukraine is bounded by the Black and Azov Seas (Fig. 1). The climate of Ukraine can be characterized as temperately continental with the exception of the southern Crimea peninsula, where a subtropical climate dominates. Most of the territory of Ukraine lies within the East European Plain and consists of regular plains with elevations of no more than 0-600 m a.s.l. among, which there are recognized lowlands and uplands. Plains are surrounded by two mountain regions which are the Carpathians (to the west) and the Crimean Mountains (to the south) (Fig. 1).

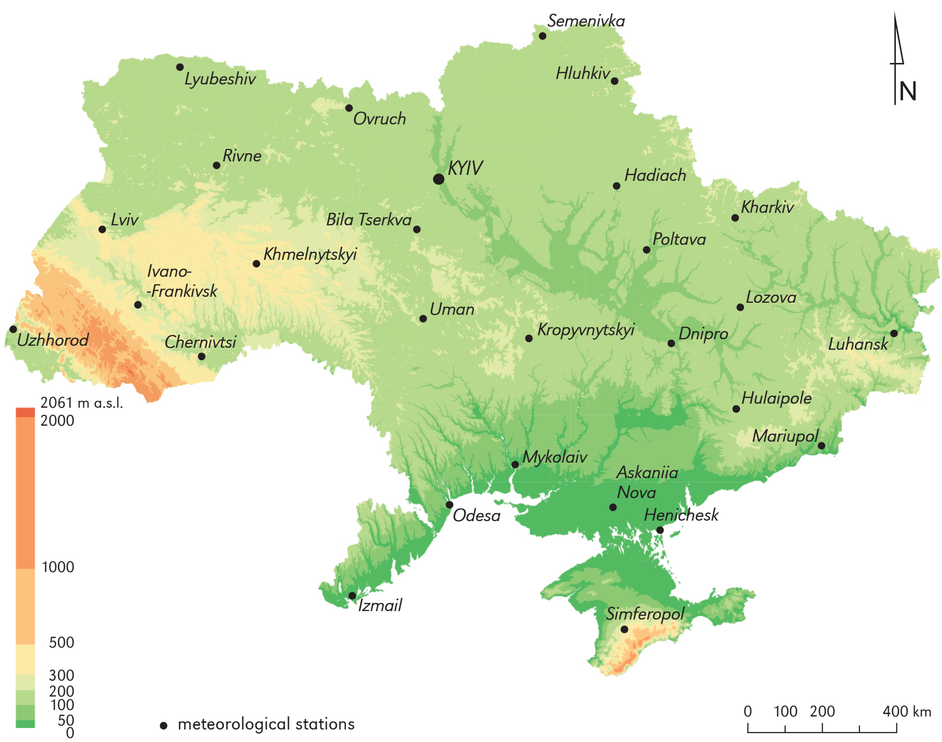

Figure 1. Location of the meteorological stations in Ukraine used in this investigation

This study uses data from 29 weather stations of the meteorological network of the Ukrainian Hydrometeorological Centre (Fig. 1). The selected stations typically experience a large range of climatic conditions. The research covered the period from June to August in the years 1961-2015 (for the station Luhansk – 1961-2013). Data of daily observations of maximum air temperature, measured at the international standard level of 2 m above ground level, are employed for the identification of HW episodes.

A meteorological phenomenon that consists of abnormally hot weather conditions, lasting several days or longer and that belongs to the atmosphere's synoptic-scale circulation is termed a heat wave. So far, there is no one objective and uniform HW definition (Meehl & Tebaldi, 2004; Monteiro et al., 2013). But daily maximum air temperature, $T_{a,max}$, measured at the international standard level of 2 m a.g.l, represents the meteorological variable which is used in numerous HW investigations. One approach to identify a HW is based on the exceedance of a fixed absolute threshold for daily $T_{a,max}$. Additional approaches are related to suited reference periods, e.g. the normal climatic period 1961-1990: exceedance of daily mean $T_{a,max}$ through daily $T_{a,max}$ by a (1) fixed percentile, (2) fixed standard deviation or (3) fixed absolute amount (Shevchenko et al., 2014). Other approaches could be used for heat wave identification for public health based not only on the air temperature, but also on other characteristics. For instance, An der Heiden et al. (2020) identified HW events based on weekly mean air temperature, but with consideration to age groups and regions. The threshold for the ≥ 85 years of age group was 19.0°C in the northern region of Germany, 19.8°C in the central, and 20.3°C in the southern region of Germany. According to the Intergovernmental Panel on Climate Change (IPCC) definition, a HW is a period of more than 5 consecutive days with daily $T_{a,max}$ ≥ 5°C above the mean daily $T_{a,max}$ for the normal climatic period 1961-1990 (Radinović & Ćurić, 2012). Shevchenko et al. (2014) substantiated that the definition of heat waves recommended by the IPCC is suitable for the investigations of HW climatology in the territory of Ukraine. This study is based on the heat wave definition described above.

Basic characteristics of HW events were calculated, including the number of heat waves for the study period and their duration, and the period of their occurrence, as well as cumulative $T_{a,max}$ for particular heat waves. Actually, the simplest (and popular) indicator to characterize the intensity of HW event at a location is the mean maximum air temperature, $T_{a,max}$. But the values of mean $T_{a,max}$ could not be use for the research of the intensity of HW events in Ukraine because of the differences in climate conditions in regions across the country. Mean monthly values of maximum air temperature at different stations in Ukraine in July of the period 1961-1990 vary significantly. For example: Semenivka, 23.6°C; Odesa, 25.5°C; Simferopol, 27.6°C; Luhansk, 28.4°C; Khmelnytskyi, 23.5°C; Dnipro, 26.7°C, etc. Therefore, in order to characterize the intensity of HWs in the Ukraine, the cumulative $T_{a,max}$ excess was applied, because Kyselý (2002) had found that it is most appropriate for this purpose. Typically, cumulative $T_{a,max}$ excess during single HWs was calculated as the sum of differences between daily $T_{a,max}$ and a threshold value, which depends on the HW 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.

The physiologically equivalent temperature is applied to the assessment of bioclimatic conditions during heat waves in present research. Physiologically Equivalent Temperature (PET) is a thermal index derived from the human energy balance. PET is defined as the air temperature at which, in a typical indoor setting (without wind and solar radiation), the energy balance of the human body is balanced with the same core and skin temperature as under the complex outdoor conditions to be assessed (Höppe, 1999; Matzarakis et al., 2018). PET values between 18.1°C and 23.0°C can be characterized as comfortable (Tab. 1).

A comprehensive review of approaches and methods of outdoor human thermal perception, conducted by Potchter et al. (2018), has shown that PET is amongst the four most widely used human thermal indices, noting that 165 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, Predicted Mean Vote (PMV) was used in 10.1%, and the Universal Thermal Climate Index (UTCI) and Standard Effective Temperature (SET*) were used in 8% and 5% of the studies respectively (Potchter et al., 2018).

The calculation of PET, based on air temperature, relative humidity, wind velocity and cloud cover data, is performed utilizing the RayMan model (Matzarakis et al., 2007). 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.

Calculated PET values at 12.00 UTC were used to analyse thermal comfort conditions during all identified HW episodes. This is consistent with many studies that assess human-biometeorological condition (Błażejczyk et al., 2013; Katerusha & Matzarakis, 2015; Owczarek, 2019; Tomczyk et al., 2020). Using daily mean PET values simplifies the analysis (as in case of maximum air temperature), therefore for evaluation of thermal stress is the more suitable PET values obtained for noon or after midday. The frequency of occurrence of days with different ranges of PET (and the corresponding grade of thermal stress) was obtained. Frequency of the days with some grade of the thermal stress during HWs was calculated as follows: the number of times some grade of the thermal stress occurred divided by the total number of days with heat waves.

Calculation of the number of heat waves and their duration, the period of their occurrence, cumulative $T_{a,max}$ during HWs, the mean and maximum PET values, as well as frequency of occurrence of particular classes of the PET at 12.00 UTC during all HWs were made using Microsoft 'Excel' software. The maps for the visualization of the results were made using Surfer software (version 13). The Kriging gridding method has been used to display the data for the geographic region of Ukraine.

Results

Spatiotemporal variability of HW events

The results indicate HW events displayed a high degree of spatial variability across Ukraine during the study period, 1961-2015. The highest number of HW events occurred in the Central region, with an absolute

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	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

maximum of 36 events at Dnipro. The number of HW events in the Central region of Ukraine varied between 21 and 36. In contrast the Southern region experienced the lowest number of events, with an absolute minimum of 3 events observed at Henichesk. The number of HW events analyzed during the study period ranged from 3 to 26 for the Southern region (Fig. 2). Some territories of the Southern region of Ukraine are under the cooling influence of the Black or Azov Sea and therefore in coastal cities a lower number of HW events were observed during the study period (3 in Henichesk, 11 in Mariupol, and 14 in Odesa). Also, a relatively large number of HW events were observed in Ovruch, Lozova and Uzhgorod (31 events each) and Kropyvnytskyi (30 events). It should be noted, these stations represent all regions except the Southern region.

The greater number of HW events identified at some stations were associated with two factors – the geographical position of the stations and the methodology used to identify the heat wave events. For instance, Uzhhorod, is situated in the westernmost part of Ukraine is isolated by the Carpathian Mountains. These mountains act as a barrier to protect the city from cold air masses. HW events in Uzhhorod are not observed to be concurrent with those in other parts of Ukraine, but in fact tend to occur at the same time as HW events in Central Europe. The same situation with Ovruch – this station is situated near to the border with Belarus, therefore some HW events, obviously, observed at the same time with heat waves in this country and caused by the same synoptic process.

In this study, a HW event at an observation site is defined as a period lasting at least 6 days for which the air temperature parameter, $T_{a,max}$ remains above the HW threshold. If a period of hot weather lasts less than 6 days, with the $T_{a,max}$ air temperature parameter dropping below the identified HW threshold, then by definition that period is not classified as a HW event. A HW event may be recorded at a particular station, however areal, sub-synoptic scale temperature fluctuations may cause a neighboring station to not concurrently record a HW event. Additionally, if the $T_{a,max}$ parameter at a particular location drops temporarily below the HW threshold

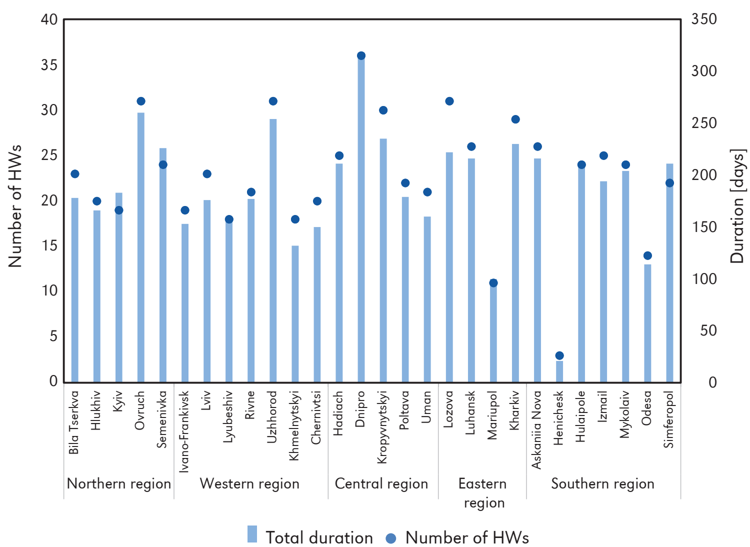

Figure 2. Number of HWs and their total duration (in days) in different parts of Ukraine for the period 1961-2015

during a long period with hot weather, that period is by definition divided into two shorter HW events. It should be noted therefore, the above mentioned can be the reason why on some stations of the region fixed higher number of HW events. It should be mentioned that disadvantages like this are inherent for nearly all heat wave definition and it is very hard to avoid such moments.

The total duration of HW events for the research period also varied significantly – from 21 days at Henichesk to 318 days at Dnipro. For all the others stations the total duration of HW events ranged between 100 and 260 days. The mean HW duration varied between 7 consecutive days in Henichesk and 10 consecutive days in Simferopol (both in Southern Ukraine). Among the selected stations, the longest HW duration was distinctly variable, ranging from 7 days (30 July–5 August 1998; 24-30 July 2001; 24-30 August 2007) in Henichesk (Southern Ukraine) to 37 days (13 July-18 August 2010) in Semenivka (Northern Ukraine).

The analysis of the spatiotemporal variability of HW events is based on results for five decades (1961-1970, 1971-1980, 1981-1990, 1991-2000, 2001-2010) and one five-years period (2011-2015). With the exception of Kyiv, Odesa and all stations of the Western region, the results show that the greatest number of HW events occurred in the decade 2001-2010 (Fig. 3). However, it should be noted that the highest number of HW events for all stations was found during the decadal periods after 1990. The highest number of HW events per decade (more than 10 events) were recorded at the stations of Ovruch, Hadiach, Dnipro, Luhansk, Kharkiv, Izmail and Simferopol during the 2001-2010 decade, and more than 10 events were recorded in Uzhgorod between 2011 and 2015. In different researched periods there were no HW events observed at some stations.

According to the values obtained of the cumulative $T_{a,max}$, the intensity of HW events was distinctly variable at different stations. The results (Tab. 2) show that HW events with the shortest duration (6 and 7 days) mostly represented the lowest intensity events. The lowest values of cumulative $T_{a,max}$ were found in Simferopol during the HW episode of 26 June to 1 July 2006 (3.2°C) and in Hlukhiv during the HW episode of 2-7 July 2001 (4.6°C). The HW events with the longest duration often represented the strongest intensity

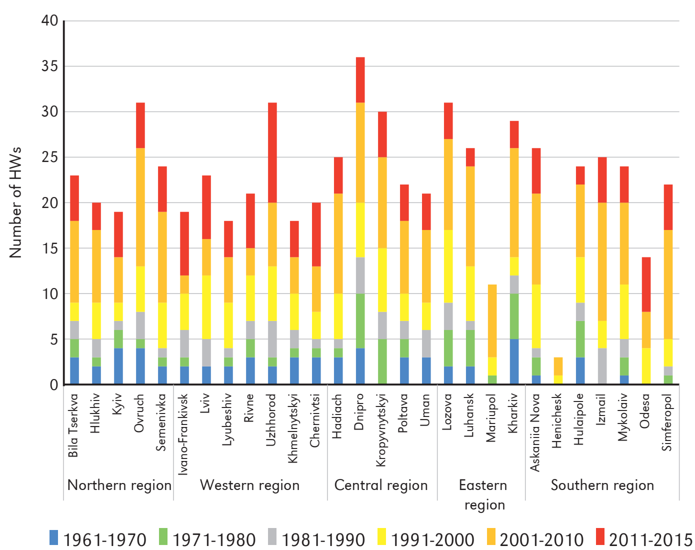

Figure 3. Number of HWs in different parts of Ukraine in the years 1961-2015

Table 2. The lowest and highest cumulative $T_{a,max}$ excess (in °C) of the respective heat wave

Region	Station	HW events with the lowest cumulative $T_{a,max}$	HW events with the highest cumulative $T_{a,max}$
Northern	Bila Tserkva	6.4 (19-24 JUL 1972)	82.3 (31 JUL-17 AUG 2010)
	Hlukhiv	4.6 (2-7 JUL 2001)	131.2 (31 JUL-18 AUG 2010)
	Kyiv	9.8 (26-31 AUG 1985)	108.6 (31 JUL-17 AUG 2010)
	Ovruch	5.6 (3-8 JUL 2001)	51.1 (25 JUL-10 AUG 1963)
	Semenivka	8.5 (16-22 JUL 1968)	255.7 (13 JUL-18 AUG 2010)
Western	Ivano-Frankivsk	7.9 (25-30 JUL 1972)	48.9 (2-16 AUG 2015)
	Lviv	7.5 (17-22 AUG 2001)	48.8 (30 JUN-11 JUL 2012)
	Lyubeshiv	7.8 (9-14 JUN 1995)	48.9 (25 JUL-7 AUG 1994)
	Rivne	7.5 (13-18 AUG 1985)	48.6 (30 JUN-11 JUL 2012)
	Uzhhorod	5.0 (16-21 AUG 1974)	55.6 (5-16 AUG 2015)
	Khmelnytskyi	6.6 (18-23 AUG 2001)	37.5 (13-24 JUN 1964)
	Chernivtsi	6.4 (31 JUL-5 AUG 2014)	45.5 (30 JUN-11 JUL 2012)
Central	Hadiach	5.9 (22-27 JUN 2006)	111.0 (31 JUL-18 AUG 2010)
	Dnipro	9.8 (12-17 JUN 1987)	122.6 (26 JUL-18 AUG 2010)
	Kropyvnytskyi	5.7 (15-21 JUL 1972)	97.8 (31 JUL-17 AUG 2010)
	Poltava	7.6 (11-17 JUN 2013)	108.4 (31 JUL-18 AUG 2010)
	Uman	8.8 (21-26 JUL 1987)	72.7 (31 JUL-17 AUG 2010)
Eastern	Lozova	7.6 (6-12 JUL 2012)	75.6 (31 JUL-12 AUG 2010)
	Luhansk	7.8 (31 JUL-5 AUG 1961)	127.8 (26 JUL-18 AUG 2010)
	Mariupol	8.5 (28 JUL-2 AUG 2002)	51.6 (28 JUL-17 AUG 2010)
	Kharkiv	7.2 (7-13 JUN 1999)	117.0 (30 JUL-18 AUG 2010)
Southern	Askaniia Nova	5.5 (6-11 AUG 2001)	72.0 (31 JUL-18 AUG 2010)
	Henichesk	14.3 (30 JUL-5 AUG 1998)	23.0 (24-30 JUL 2001)
	Hulaipole	6.0 (18-23 AUG 2001)	66.5 (30 JUL-12 AUG 2010)
	Izmail	6.2 (6-11 AUG 2001)	46.3 (16-25 JUL 2007)
	Mykolaiv	8.0 (18-23 AUG 2001)	67.5 (31 JUL-17 AUG 2010)
	Odesa	6.4 (31 JUL-5 AUG 2014)	46.4 (5-16 AUG 2010)
	Simferopol	3.2 (26 JUN-1 JUL 2006)	70.7 (30 JUL-18 AUG 2010)

HW episodes. The highest intensity HW event in this study was also the longest duration event (37 days). The largest recorded value of cumulative $T_{a,max}$ excess (255.7°C) occurred in Semenivka during the period 13 July to 18 August 2010. For 18 of the 30 selected stations in Ukraine the highest cumulative $T_{a,max}$ excess was calculated for this extreme HW event in the summer of 2010.

The highest intensity HW events recorded at stations from the Western region of Ukraine during the study were characterized by lower values of cumulative $T_{a,max}$ (ranging from 37.5°C (13-24 June 1964) at Khmelnytskyi to 55.6°C (5-16 August 2015) at Uzhhorod) when compared to values calculated across other regions of Ukraine. It should also be noted that HW events in the western part of Ukraine were not observed during the same periods as those that occurred in other regions of the country, but were associated with HW events in Central Europe. For example, the HW event of August 2015 was the most intense event recoded at the Ukrainian locations of Ivano-Frankivsk (cumulative $T_{a,max}$ 48.9°C) and Uzhgorod (cumulative $T_{a,max}$ 55.6°C). The HW event occurring at the end of July–first half of the August 1994 was the most intense event at the location of Lyubeshiv (cumulative $T_{a,max}$ 48.9°C).

Thermal comfort conditions during heat wave cases

The mean PET value during HW events for Ukraine during the period 1961-2015 was 38.0°C. Mean values ranged from the west to the south and south-east (Fig. 4). Over a major part of the country mean PET values during HWs varied from 35.1°C to 41.0°C (strong heat stress). Lower mean PET values were found for some stations from the western region (Lviv, Rivne, Khmelnytskyi) and mean PET values higher than 41.0°C (extreme heat stress) were found in Luhansk (eastern region) and Henichesk (southern). The highest mean PET values for individual HW events ranged from 38.0°C in Khmelnytskyi to 48.0°C in Chernivtsi. At the large majority of stations (80%) maximum values exceeded 41°C, i.e. they exceeded the threshold of extreme strong stress. At 35% of stations, the maximum mean PET value was found during the HW event in 2010 (Fig. 5).

The maximum PET values during all HW episodes for the period 1961-2015 ranged between 43.7°C and 56.0°C. It should be noted that for all stations in Central and Eastern regions the maximum PET values exceeded 50°C, while maximum PET values for the majority of stations in the Western and Northern region were lower than 50°C.

During HW episodes days with strong heat stress (PET values of 35.1-41.0°C) were recorded the most frequently at nearly all

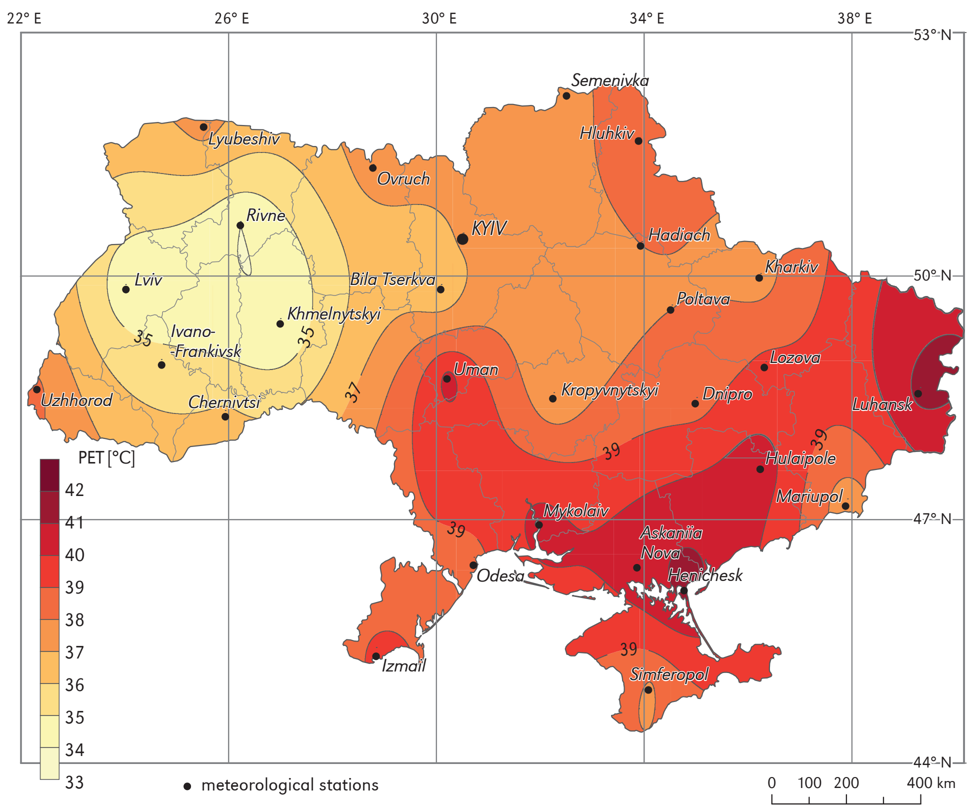

Figure 4. Mean PET value (°C) at 12.00 UTC for all HWs in the years 1961-2015

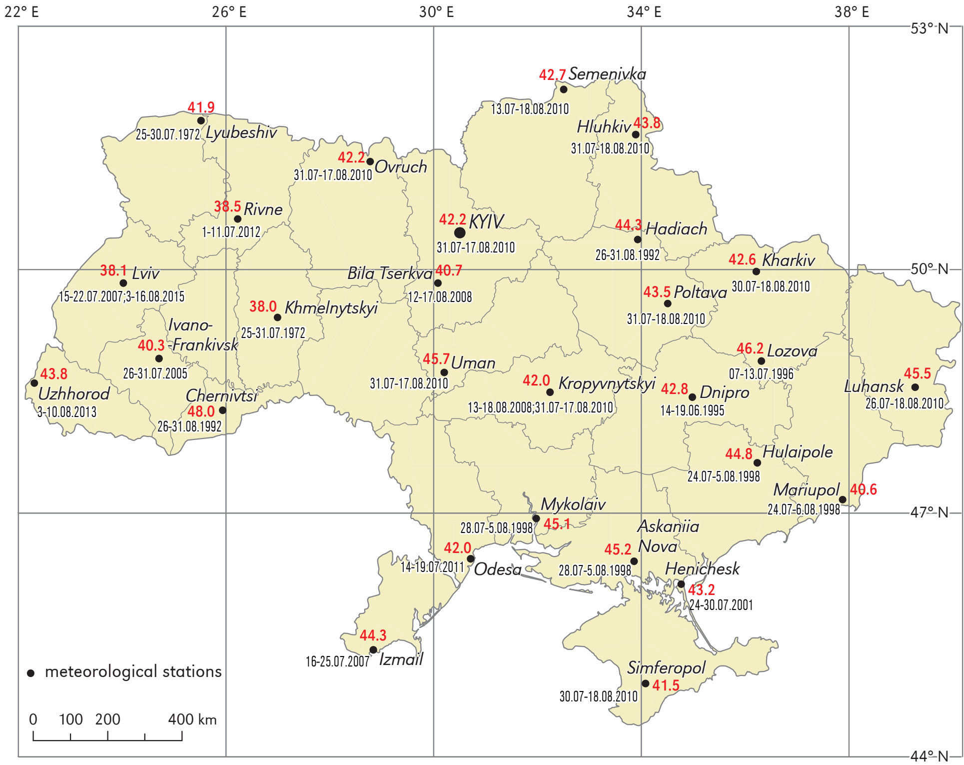

Figure 5. The highest mean PET value (°C) at 12.00 UTC with date of occurrence of the HW in the years 1961-2015

stations (Fig. 6). At 51.7% of stations, such days constituted more than 50% of all analyzed days. The frequency of days classified as days with moderate heat stress (PET values of 29.1-35.0°C) was highest at the Western region stations of Ivano-Frankivsk, Lviv, Rivne, Khmelnytskyi with values ranging between 44.6% and 48.4%. During HWs, days classified as days with extreme heat stress (> 41.1°C) were recorded the most frequently at Uman (44.4%), Luhansk (56.0%), Askaniia Nova (49.1%) and Henichesk (57.1%). The highest number of days during heat waves belongs to the grades of moderate, strong and extreme heat stress. The frequency of such days was very high and varied from 85.3% in Rivne to 100% in Poltava and Henichesk. The frequency of such days categories are lower than 90% only for three stations of Western region. Days with slight heat stress (23.1-29.0°C) ranged from 0.5% in Luhansk and Hulaipole to 12.1% in Khmelnytskyi. No days of this category were recorded in Poltava and Henichesk.

Days classified as days with no thermal stress during HW episodes were recorded at 11 stations from all regions, but the frequency of such days was very low and ranged between 0.4% (Semenivka and Kropyvnytskyi) and 2.3% (Rivne). One day during the study period was classified with slight cold stress at Rivne, Khmelnytskyi and Kharkiv. At all stations, these were the last days of the HW episodes. The demise of the HW events was typically characterized by a fall in air temperatures (and decrease in the PET values) due to rainfall associated with the passage of atmospheric frontal systems through Ukraine.

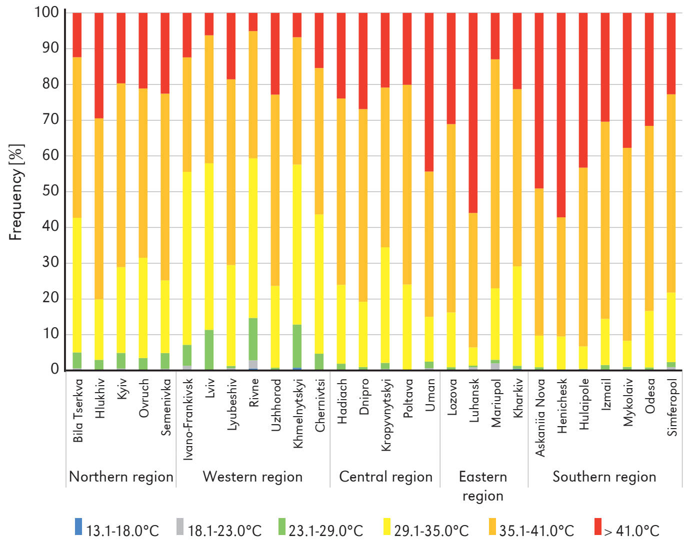

Figure 6. Frequency of occurrence of particular classes of the PET at 12.00 UTC during all HWs in the years 1961-2015 in different parts of Ukraine

Discussion

The results obtained in this research showed that the highest number of HW events at all the stations in Ukraine was found after 1990 and the greatest number of HW events occurred in the decade 2001-2010 (with the exception of Kyiv, Odesa and stations of the Western region). During the last decades, the frequency of heat waves and their duration has increased worldwide (Basarin et al., 2016; Fenner et al., 2019; Tomczyk et al., 2019; Wibig, 2017; Yu et al., 2020) Two powerful heat waves, which both covered a large but individually different areas of Ukraine, were found during the period 1961-2015. The HW event of the late of July – mid August 2010, identified as the longest and strongest at nearly all the stations of the northern, central, eastern and southern regions of Ukraine. The HW event of the first half of August 2015, which covered a large area of the western region, as well as at some parts of north and southwest of Ukraine.

The lowest number of HW events occurred at the southern region coastal cities of Henichesk, Mariupol and Odesa. Three, eleven and fourteen HW events were recorded respectively for the study period. The total duration of HW events at locations for the research period varies significantly, ranging from 21 days in Henichesk to 318 days in Dnipro. In contrast the total duration of HW events for the study period was lower in Poland varying between 4 days (in Łeba) and 228 days (in Słubice) (Tomczyk et al., 2020).

For the identified heat wave cases, and the corresponding mean PET values calculated for the events, the eastern and southern regions of Ukraine (with the exception of coastal stations) are the territories which represent the greatest risk to the population with regards to heat stress exposure. Lower heat influence is observed in the western region of Ukraine and coastal cities due to the cooling influence of the Black or Azov Sea.

The strongest HW event for the territory of Ukraine located at the left bank of river Dnipro, as well as some stations situated on the right bank of the river (in general, for 18 of the 30 researched stations) was HW events of the end of July – first half of August 2010. The cumulative $T_{a,max}$ during this HW event reached very high values at some stations (131.2°C at Hlukhiv, 127.8°C at Luhansk, 122.6°C at Dnipro, 117.0°C at Kharkiv, 111.0°C at Hadiach, 108.6°C at Kyiv, and 108.4°C in Poltava), with the largest recorded value excess (255.7°C) occurred in Semenivka. The station is located in the north of Ukraine near the border with Russia, where in Western part a particularly extreme heat wave occurred during July and August 2010 (Barriopedro et al., 2011; Rahmstorf & Coumou, 2011). Owing to its dimension in terms of amplitude and spatial extent, this heat wave was evaluated as a mega HW event by Barriopedro et al. (2011). Revich and Shaposhnikov (2012) and Tomczyk (2017) reported a HW duration in Moscow of 45 consecutive days in association with this mega event. Basarin et al. (2020) outlined that the comparison between very intensive HW events in 2003 and 2010 showed that the latter was more extreme due to anomalies of high-temperature as well as the area affected. The summer temperatures in Europe for 2010 were on average 0.2°C higher than in 2003. The area exposed by the extreme heat was more than two million square kilometers, and the very high temperatures lasted between 15- and 61-day averages. The highest duration of the 2010 HW event in Ukraine (37 days) occurred at the station of Semenivka (situated on the north-east of the territory, closer to Russia, were the geographic centre of this HW event was situated). Weather conditions were anomalously hot for a long time because of a blocking anticyclone situated over Moscow as well as the central part of European Russia (Shevchenko et al., 2013; Konstantinov et al., 2014).

Heat wave of July – first half of August 2010 was not only the longest and strongest for nearly all the stations of the Northern, Central, Eastern and Southern regions of Ukraine, but also has produced the most strenuous human-biometeorological conditions since 1961. Strong and extreme heat stress prevailed at 12.00 UTC during the period from 31 July to 12 August at the stations where the heat wave was observed. Extreme heat stress was observed every day at 12.00 UTC during 31 July–12 August at Poltava, Lozova, Luhansk, Kharkiv, Hulaipole and Mykolaiv. One day with strong and others with extreme heat stress levels were found in Kropyvnytskyi, Hlukhiv and Dnipro.

The strongest HW events recorded at stations across the western region of Ukraine are characterized by lower values of cumulative $T_{a,max}$, when compared with events recorded in other regions of Ukraine. For the western region of Ukraine the most well-known HW event of August 2015 was strongest at the observing stations at Ivano-Frankivsk and Uzhhorod, but it was characterized by a lower heat load when compared with the heat wave of the summer of 2010. During the period from 5 to 14 August 2015 mean PET values at 12.00 UTC were generally associated with strong heat stress levels, with one station reporting an extreme heat stress level. Mean PET values at 12.00 UTC ranged between 37.2°C (recorded at Khmelnytskyi) and 42.0°C (recorded at Uzhhorod) during this period, while for the period 31 July to 12 August 2010 the mean PET values at 12.00 UTC ranged from 39.8°C at Mariupol to 47.9°C at Luhansk. PET values corresponding to extreme heat stress and strong heat stress levels only occurred at two stations. All of the stations of the western regions (with the exception Uzhhorod and Chernivtsi) during the HW events were characterized by lower PET values because of climatic conditions. It is well-known that air temperatures in summer months across the western region are lower compared to the other regions of Ukraine. For instance, mean air temperatures for the period 1961-1990 for the station at Lviv is 16.7°C, for Ivano-Frankivsk – 17.3°C, for Lyubeshiv and Rivne – 17.2°C, Khmelnytskyi – 17.4°C (Western region), while mean air temperature in Uman – 18.3°C, Hadiach – 18.7°C, Kropyvnytskyi – 19.3°C, Poltava – 19.4°C, Dnipro – 20.5°C (Central region); in Kharkiv – 19.6°C, Lozova – 20.0°C, Luhansk – 20.7°C, Mariupol – 21.2°C (Eastern region); Hulaipole – 20.2°C, Simferopol – 20.6°C, Odesa – 20.7°C, Izmail – 21.0°C, Askania Nova – 21.3°C, Mykolaiv – 21.5°C, Henichesk – 21.9°C (Southern region).

It should be noted that HW events in the western part of Ukraine were generally observed to not be concurrent with those in other parts of the country, but tended to occur at the same time as HW events in Central Europe: in August 2015 the strongest recorded HW event for the research period was recorded at the observing sites at Ivano-Frankivsk and Uzhhorod, HW occurred at the end of July – first half of the August 1994 was the strongest for Lyubeshiv. The HW events of July and August 1994 and August 2015 belong to the six mega-heat wave events recorded in Poland since the end of World War II to 2015 (Krzyżewska & Dyer, 2018) and the 2015 mega-heatwave event had a longer duration over a larger area than any previous event. The average temperature during heat wave 2015 was the highest since the 1980s at most Polish meteorological stations, some Ukrainian stations, as well as in Belarusia and Lithuania (Krzyżewska & Dyer, 2018). The HW in August 2015 has been noted as one of the most severe heat waves in central and eastern Europe (Hoy et al., 2017). The mean PET values at 12.00 UTC during the HW in August 2015 in the Western region of Ukraine were slightly higher than the mean PET values in neighboring Poland (Tomczyk et al., 2020). Krzyżewska et al. (2020) and Tomczyk et al. (2020) evidenced that the most strenuous conditions during the HW event of 2015 in Poland was observed on 7 and 8 August. Analysis of PET values of the territory of Ukraine did not confirm these dates as days with the highest thermal load on humans during this heat wave event. High PET values at different stations across Ukraine were found to occur in different days.

An extraordinary heat wave also occurred in the Czech Republic in July and August 1994 (Kyselý, 2002). According to Lhotka and Kyselý (2015), the HW event that occurred in summer 1994 was the strongest for Central Europe, followed by the 2006 HW event and both these events were considerably more extreme than the HW events in the summers of 2003 and 2010. The occurrence of these heat waves also in association with a strong high-pressure system. Tomczyk et al. (2019) have found that the high-pressure system persisted over a major part of the north, central and east Europe, and the anticyclonic centre (> 1020 hPa) was located over western Russia during the HW event of 2015. Maps of 500 hPa geopotential height indicated an upper-level ridge over central Europe and temperature anomalies at 850 hPa confirmed the warm air mass advection. Warm air masses covered central and south Europe during summer 2015. Tomczyk et al. (2019) showed that anticyclonic blocking patterns in central Europe in summer inhibit the zonal flow of air masses and intensify the meridional flow, which lead to the advection of tropical air masses.

In the analyzed years, the mean PET value during HW events for the territory of Ukraine was 38.0°C. Over a major part of the country mean PET values for all HW events varied from 35.1°C to 41.0°C and the highest mean PET values for individual HW events ranged between 38.0°C and 48.0°C. PET values during HW events obtained for Poland for nearly the same period (1966-2018) are slightly lower (Tomczyk et al., 2020), which was anticipated given the climate there with lower air temperatures. For instance, the mean PET value during HW events in the territory of Poland was 36.5°C, mean PET values varied from 32.7°C to 37.8°C, the highest mean PET values for HWs ranged from 36.2°C to 44.9°C (Tomczyk et al., 2020).

During HW events in Ukraine, days with strong heat stress were experienced most frequently at nearly all stations. At 51.7% of stations, strong heat stress levels at 12.00 UTC constituted more than 50% of all HW days. At nearly all the stations the greatest number of days during heat waves belongs to the grades of strong and extreme heat stress. The contribution of such days varied between 40.7% in Rivne and more than 93.0% in Luhansk and Hulaipole. The strenuous human-biometeorological conditions during HWs were also observed in the other countries. Strong and extreme heat stress also prevailed at nearly all the stations at 12.00 UTC during HW events in Poland (Tomczyk et al., 2020).

There are significant differences in the thermal bioclimate of big cities and residents of urban centers are the most vulnerable during heat wave events. Therefore, investigations (with the objective to analyze thermal comfort conditions over a large area or over different regions) should be based on the data from weather observation networks (Tomczyk et al., 2020), not on the data of urban stations, which are affected by local microclimate of urban structures. The present study based on the data from the weather stations of the meteorological network of the Ukrainian Hydrometeorological Centre. The stations are situated in open spaces with some distance to the nearest trees and buildings and represent the climatic conditions of the regions where they are situated. The data from these stations are used as a basis for establishing the characteristics of the climate of Ukraine (Lipinskyi et al., 2003). Thus, the spatio-temporal distribution of PET values obtained in this research study has been influenced by differences in climate conditions of the territory of Ukraine rather than local micro-climatic factors. But certainly, it would be an asset to have future investigations of thermal comfort conditions during HW events in Ukraine devoted to the assessment of differences in thermal bioclimate across various urban structures, such as Kyiv or others big Ukrainian cities.

Conclusion

This study presents an important first step for the assessment of human thermal load during HW events across Ukraine predicted on the application of thermal indices which are (in tern) based on the human energy budget. The study has shown an increase in HW events in the territory of Ukraine over the last decades. Coastal territories of the southern region of Ukraine were characterized by the lowest number of HW events during the study period. HW events in the western part of Ukraine were generally observed to not be concurrent with those in other parts of Ukraine but tended to occur concurrently with HW events in Central Europe. East and south Ukraine (with the exception of coastal stations) experienced the most strenuous human-biometeorological conditions during HW events. Lower mean PET values were found for the western region of the country. The obtained results suggest that the HW event of 2010 (which covered the territory of the Northern, Central, Eastern and Southern regions, except of Henichesk station) was the longest and the most strenuous HW in human-biometeorological terms since 1961. The findings obtained in this study can be used in public health protection, regional and urban planning, various aspects of tourism and recreation areas, and research in climate change.

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

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