Pol. J. Environ. Stud. Vol. 32, No. 4 (2023), 3175-3183
DOI: *10.15244/pjoes/161665* ONLINE PUBLICATION DATE: 2023-05-10

Original Research

Heatwaves' Characteristics Detected by Heat and Cold Wave Index in Ukraine over the Last Four Decades

Anatolii Kornus[1]*, Olesia Kornus[1], Serhii Klok[2], Olena Danylchenko[1], Olena Babenko[3]

[1]Department of General and Regional Geography, Sumy State Pedagogical University named after A. S. Makarenko, 87 Romenska St., Sumy, 40002, Ukraine
[2]Department of Climatic researches and weather long-range forecasts, Ukrainian Hydrometeorological Institute, 37, Nauky Av., Kyiv, Ukraine
[3]Department of Human Biology, Chemistry and Methodology of Teaching Chemistry, Sumy State Pedagogical University named after A. S. Makarenko, Ukraine

Received: 12 November 2022
Accepted: 25 February 2023

Abstract

The purpose of this research is to analyze the characteristics of heatwaves during the warm period of the year as a manifestation of climatic changes in Ukraine. It was also our goal to establish how reliable Heat and Cold Wave Index (HCWI) from European Drought Observatory (EDO) is as a tool for heatwaves analysis. To extract the frequency and duration of heatwaves the percentile thresholds of 90th were used. The data from Ukraine' weather stations since 1980 to 2021 were under analysis. There are 83 heatwave (HW) recorded in Ukraine. At the same time, for the first half-period (1980-2000) 29 events of heatwaves were recorded, and for second half-period (2001-2021) − already 54 events. The duration of heatwaves increased during the study period. If for 1980-2000 the average duration of the heatwaves was 3.8 days, then for 2001-2021 the average duration increased to 4.3 days. The average maximum length of heatwaves increased more significantly − from 7.4 to 11.5 days in the second half-period. The intensity of heatwaves was evaluated by temperature extreme. The average maximal temperature (1980-2021) during the heatwaves over Ukraine is 32.2ºC. The hottest HW event for the study period had maximum daily temperature of 41.4ºC (2010). For the first time, HCWI was used to determine the frequency, duration and intensity of heatwaves in Ukraine. HCWI can also be applied to study climate changes, determine the period of droughts, the adaptation of the population to heat stress and the healthcare system to its consequences.

Keywords: heatwave, Ukraine, percentile thresholds, frequency, duration, intensity, warm period

*e-mail: kornus@sspu.edu.ua

Introduction

The Earth's average surface temperature has risen about 1ºC since the late of 19th century. Most of the warming occurred in the past 40 years, with the seven most recent years being the warmest. The years 2016 and 2020 are tied for the warmest year on record. But not all parts of the world are set to be hit equally. Europe, in fact, has already passed the 1.5ºC threshold and is currently 2.2ºC warmer than it was before the industrial revolution. With temperatures on the rise it is clear that climate change is already creating serious consequences for human's life due to increasing in extreme weather events and changes globally. Climate change is the single biggest health threat facing humanity [1] because the effects of climate change will continue to worsen human health through heat stress, air pollution, increasing of diseases and mortality rate, hunger and displacement, etc.

There is a global warming impact also observed in Ukraine. Over the past twenty years, every year in Ukraine has been warmer than the climate normals, and 2020 became the hottest year not only in Europe, but also in Ukraine, exceeding the average air temperature of 1961-1990 by 2.8ºC. Ukraine has become more likely to experience a range of climate change-related impacts, such as periods of extreme heat, devastating fires that have killed people, or severe droughts. One of the signs of climate change is an increase in the risks of climate events such as heatwaves (HWs). HWs have become more frequent, longer, more severe, and more intense from year to year over the period 1981-2021.

It can be said that the first step to control or at least to reduce the harm caused by these climatic phenomena are by definition, recognition and identification of its features by scientific methods.

The aim of the article is to analyze heatwaves characteristics, namely their frequency, duration and intensity in the warm period of the year as a manifestation of climatic changes in Ukraine. Also, the purpose of the article was to establish how the heatwaves detected by European Drought Observatory (EDO) via Heat and Cold Wave Index (HCWI) correspond to those detected by the Ukrainian researchers according to the data obtained from the weather stations directly.

Today is no comprehensive and universal definition of a heatwave (HW). In the latest World Meteorological Organization (WMO) edition on the subject, we again see a very broad definition of HWs as a marked unusual hot weather (Max, Min and daily average) over a region persisting at least two consecutive days during the hot period of the year based on local climatological conditions, with thermal conditions recorded above given thresholds [2]. In accordance with Glossary of Meteorology published by American Meteorological Society [3] "heatwave" is a period of abnormally and uncomfortably hot and usually humid weather.

First this term ("hot wave") was rigidly defined in 1900 by A.T. Burrows [4] as a spell of three or more days on each of which the maximum shade temperature reaches or exceeds 90ºF (32.2ºC). Then in the early twentieth century, R. Ward has defined a HW as an unpleasant period of high temperature during the warming seasons lasting more than one day [4].

Different researchers and national weather services in different countries use various definitions of HWs, as well as there are many criteria for HW determining, so we will focus only on European ones.

For example, J. Kyselý [5] uses a different definition for HW research in the Czech Republic, based on two extreme temperatures (T1 and T2). A HW is defined as a period during of which: 1) the daily maximum air temperature is above T1 for at least 3 consecutive calendar days; 2) the average maximum air temperature for the entire period is above T1; 3) the maximum air temperature does not fall below T2. In this case, T1 = +30.0ºC and T2 = +25.0ºC.

In the Netherlands, a HW is defined as a period of at least five consecutive days in which the maximum temperature in De Bilt weather station (where the headquarters of the Royal Netherlands Meteorological Institute is located) exceeds 25ºC, provided that on at least three days ("tropical days") in this period the maximum temperature exceeds 30ºC [6]. This definition of a HW is also used in Belgium and Luxembourg. In Denmark, a national HW is defined as a period of at least 3 consecutive days of which period the average maximum temperature across more than fifty percent of the country exceeds 28ºC [7]. For Bulgaria proposed to consider as a heatwave count of days when air temperature is ≥32, 34, 36, 38, and 40ºC for at least 6, 5, 4, 3, and 2 consecutive days, respectively [8].

In Greece a HW is defined as three consecutive days at or above 39ºC and a minimum temperature in the same period at or over 26ºC, with no winds or with weak winds, and the above conditions being observed in a broad area.

A well-known definition of HW is as five or more consecutive days of prolonged heat in which the daily maximum temperature is higher than the average maximum temperature by 5ºC or more (TXA5) [9]. This criterion is also used by Ukrainian scientists [9-12].

In general, all the above mentioned definitions of HW can be united in one group, where HW detection is based on regionspecific absolute and numerical thresholds.

In the second group, researchers define a HW based on relative and percentile thresholds with a comprehensive vision [13-17]. It should be noted that absolute numeric thresholds are insufficient for analyzing a large country such as Ukraine. Today a common way of ascertaining thresholds is based on selecting the tail of distributions for temperature. In several studies, 10 relative based thresholds were applied to detect HWs [18-21]. Statistical partitions such as by quartiles or percentiles of the distribution have provided a means for evaluating extremes.

H. De Boeck et al. [22] used relative temperature limits for detecting HW. For each weather station and each day of the year, a 90% probability of maximum temperature is calculated. Days on which maximum temperatures exceed these calculated values are called "hot days". According to this method, a HW is a period of at least 7 consecutive hot days. If during a HW with 7 consecutive hot days, there is one day with temperatures below the relevant limit values, then this period is still considered as one HW (for HW of 15 days, 2 non-consecutive days with lower temperatures are allowed).

The study by R. Mandal and coauthors showed that 95th percentile of daily maximum temperature and its duration equal to or more than 6 days are suitable to determine a HW [23]. In another study, HWs have been defined using a period more than three consecutive days and above percentile threshold of 90th in daily maximum temperature [24]. Usually a HWs have been defined as temperatures above the 90th percentile (TX90p), persisting for three or more days [25, 26, 27]. This method of HW detection was used for multitude investigations [14, 15, 28], including and the one used in our study. The use of calendar day percentile-based threshold values to determine hot (as well as cold) days means that the temperature anomalies that are detected are specific for the time of year, and for the geographic location.

Material and Methods

This study is based on the Heat and Cold Wave Index (HCWI) that is implemented in the Copernicus European Drought Observatory. HCWI is used to detect and monitor periods of extreme-temperature anomalies (i.e. heatwaves) that can have strong impacts on human activities and health. This is one of the climate indexes that takes into account both HW duration and intensity. The HCWI indicator is computed for each location (grid cell), using the methodology developed by Lavaysse et al. [25], and based on the JRC's MARS AGRI4CAST database of daily meteorological observations.

In accordance with the factsheet of EDO Indicators, HW defined as events of at least three consecutive "hot" days. In this context, a "hot day" is a day with both daily air minimum and maximum temperatures (Tmin and Tmax) are above their daily threshold values, calculated as the 90th percentile values of Tmin and Tmax for that calendar day during the 30-year climatological baseline period (1981-2010). The JRC MARS Meteorological Database contains meteorological observations acquired from weather stations, have an irregular distribution and density in space. Data of a single weather station are representative for the location of that station only. To construct weather data for locations in between stations a conversion is needed. Interpolation is one of the methods to do this. Convertion of irregularly distributed station data to regularly distributed data organized as a grid with side by side grid cells of 25 kilometers in width and 25 kilometers in length was made by MARS Crop Yield Forecasting System (MCYFS). The grid cells covers the entire all territory of Ukraine.

The daily threshold values for Tmin and Tmax for that calendar day are defined as the 90th percentile of the 330 respective temperature values in an 11-day window centered on that day for all years in the above-mentioned baseline period. When two successive HWs are separated in time by one day, these are considered to be mutually dependent events, and so are merged ("pooled") as a single event. The duration of HW is computed in days (not counting "pool" days) of the detected waves. In order to highlight the events with the most potential human impact, HWs are detected during the "extended summer" period (i.e. from April to September, the six hottest months over Europe). Fig. 1 illustrated of the indication for two HWs: with pool (HW1) and single event (HW2). As we said, by definition, the minimum duration of a HW is three days, but for Ukraine duration of HWs increasing to fifteen days. For durations under three days, the affected grid-

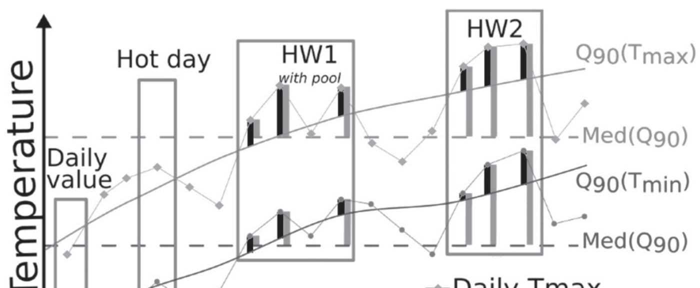

Fig. 1. Schema of the detection method of heatwaves, based on temperature anomalies of a calendar day threshold: Q90 (Tmax) and Q90 (Tmin) or based on the constant climatological threshold defined by the median of the daily quantiles: Med (Q90 (Tmax)) and Med (Q90(Tmin)) [25].

cells are indicated with dotted stripes in order to flag areas where HWs may potentially be starting. As can be seen, their intensity can also be quantified, based on anomalies of Tmin and Tmax from calendar day Q90(Tmax) − black column or based on the constant threshold defined by the median of the daily quantiles Med(Q90) − grey column [25].

The interpolation procedure generates gridded datasets of observed weather. In order to describe weather at a spatial domain larger than the grid size and to answer questions like e.g.: "How many HWs were in Ukraine during the last year?" gridded weather data are aggregated. Grid cells (or part of grid cells) where detected HW that fall inside Ukraine are used to calculate the aggregated values of the HW as well as their duration and intensity over Ukraine. A dedicated software package called Aggregator is developed by MCYFS to do all calculations [29].

Thus, the percentile thresholds were applied on daily maximum temperature time series of the weather stations of Ukraine to detect HWs in the warm period of the year between 1980-2021, and ultimately to understand the spatial distribution of the changes in terms of characteristics of HWs over Ukraine.

In the course of the work, well-known methods of mathematical and statistical analysis were used, implemented through the built-in functions of the software MicrosoftExcel and Statistica from StatSoft Inc.

Results and Discussion

Frequency, Duration and Intensity Heat Waves over Ukraine Detected by HCWI

As well-known, HWs have three main characteristics: a) Frequency: the number of HWs that occur every year; b) Duration: the length of each individual HW, in days, and c) Intensity: how hot it is during the HW.

As a result of analysis of the series of daily air temperature for 1980-2021 there are 83 HW events that met the criteria for defining this event, which is used in this study, were recorded in Ukraine (on the average 2 events per year). At the same time, the uneven manifestation of this atmospheric phenomenon in time is clearly traced with the allocation of two half-periods, the duration of which is 21 years. For the first half-period (1980-2000) 29 events of HW were recorded, and for second half-period (2001-2021) − already 54 events (Fig. 2). It should be noted that 1-2 events of HWs were usually recorded in Ukraine per year until 2001, but in the second half-period their frequency increased to 2-3 events, and in some years reached to 4-5 events per year. Fig. 2 shows changes in the number of HW per year (frequency) over Ukraine during 1980-2021.

As can be seen from Fig. 1, an intensive increase in the number of heat waves on the territory of Ukraine has occurred since the end of the last century (before that time, their number was consistently minimal). Accordingly, the linear trend of the last period is somewhat more intense than the trend that describes the entire period of 1989-2021.

According to the EDO methodology, the minimum duration for which the HW is recorded is 3 days. The maximum length of HW over Ukraine for the study period 1980-2021 ranged from 4 (1984) to 20 (2010 and 2013) days (Fig. 3). So, the average duration is 4.2 days, and the average maximum length of HW is 9.45 days. The results of the study show that all indicators characterizing the duration of HW increased during study period. If for 1980-2000 the average duration of heatwaves was 3.8 days, then for 2001-2021 the average duration increased to 4.3 days. The average maximum length of HW increased more significantly − from 7.4 to 11.5 days in the second half-period.

To characterize the intensity of HW, as a rule, the cumulative Tmax during a single HW is used. J. Kyselý [5] notes that this characteristic is the most convenient for wave intensity evaluation. Usually, the

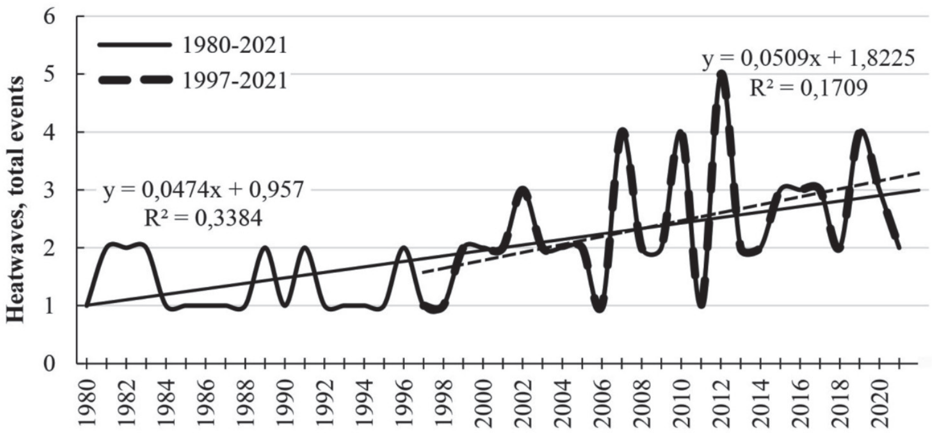

Fig. 2. Heatwave frequency over Ukraine (Source: EDO Database)

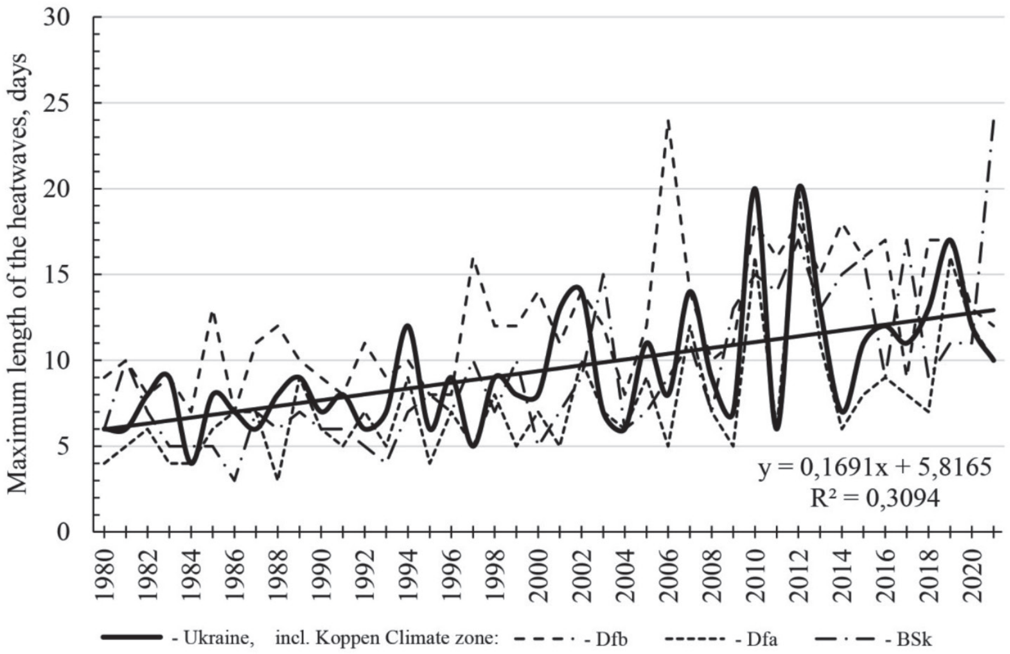

Fig. 3. Maximum length of the heatwaves over Ukraine and per Köppen Climate zone (Own generation from EDO Database). The maximum duration of the heatwaves per Köppen Climate zone are given by dotted stripes. The maximum length of the heatwaves during 1980-2021 over Ukraine and linear trend for it are shown in bold black.

cumulative Tmax during an individual HW is calculated as the sum of the differences between the maximum daily air temperature and a certain limit value, depending on the HW definition. However, such an indicator can also be the temperature of hottest day of the HW event. It was used in a recent work about HW in Ukraine [27]. The intensity of the HW determined according to EDO as the maximum air temperature extreme. Over Ukraine (Fig. 4), the hottest HW events for the study period were with a maximum daily temperature of 41.4ºC (2010), and mean (1980-2021) temperature extreme of the HW over Ukraine is 32.2ºC.

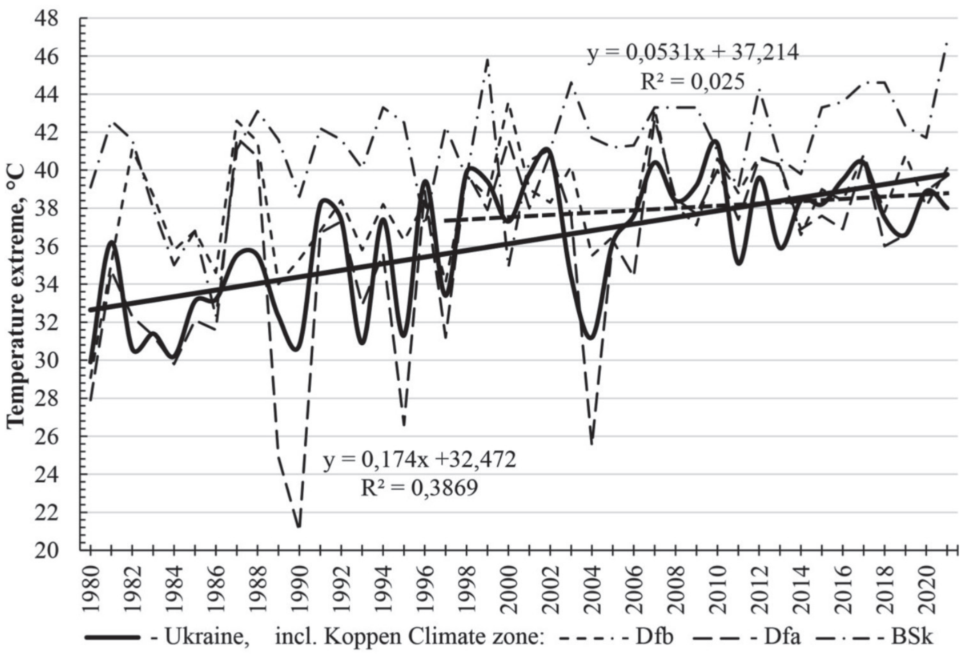

Fig. 4. Temperature extreme of the heatwaves over Ukraine and per Köppen Climate zone (Own generation from EDO Database). The temperature extreme of the heatwaves per Köppen Climate zone are given by dotted stripes. The temperature extreme of the heatwaves during 1980-2021 over Ukraine and linear trend for it are shown in bold black.

The “coolest” HWs were in 1980, 1982, 1984 and 1990, and the hottest HW were in 2022, 2007 2010 and 2017, when the temperature extreme exceeded 40ºC. That was expected that the hottest waves are in the south of Ukraine, where the temperature extreme reached 45.8ºC (1999) and 46.8ºC (2021).

It should be noted that, in addition to Ukraine as a whole, the EDO makes it possible to evaluate the characteristics of HWs per Köppen climatic zones.

Heat Waves over Ukraine Detected by Local Weather Stations Data

Of course, there is nothing more reliable than calculations made from the data received directly from weather stations. However, for many interested in HW, a number of problems arise in this case: for example, access to data that are not publicly available, as well as the need to carry out rather complex of calculations and estimations. At the same time EDO map generator allows to create a maps containing large amounts of daily geographic data regarding climate, incl. detecting of the heat (as well as cool) waves. The maps generated in Lambert Equal Area projection using the current content of the database and are of high quality. Such functionality is rare on the internet were quick and small resolution maps are the standard.

In addition, data acquisition and meteorological calculations takes a lot of time, but, as well known, information is best obtained quickly, especially when

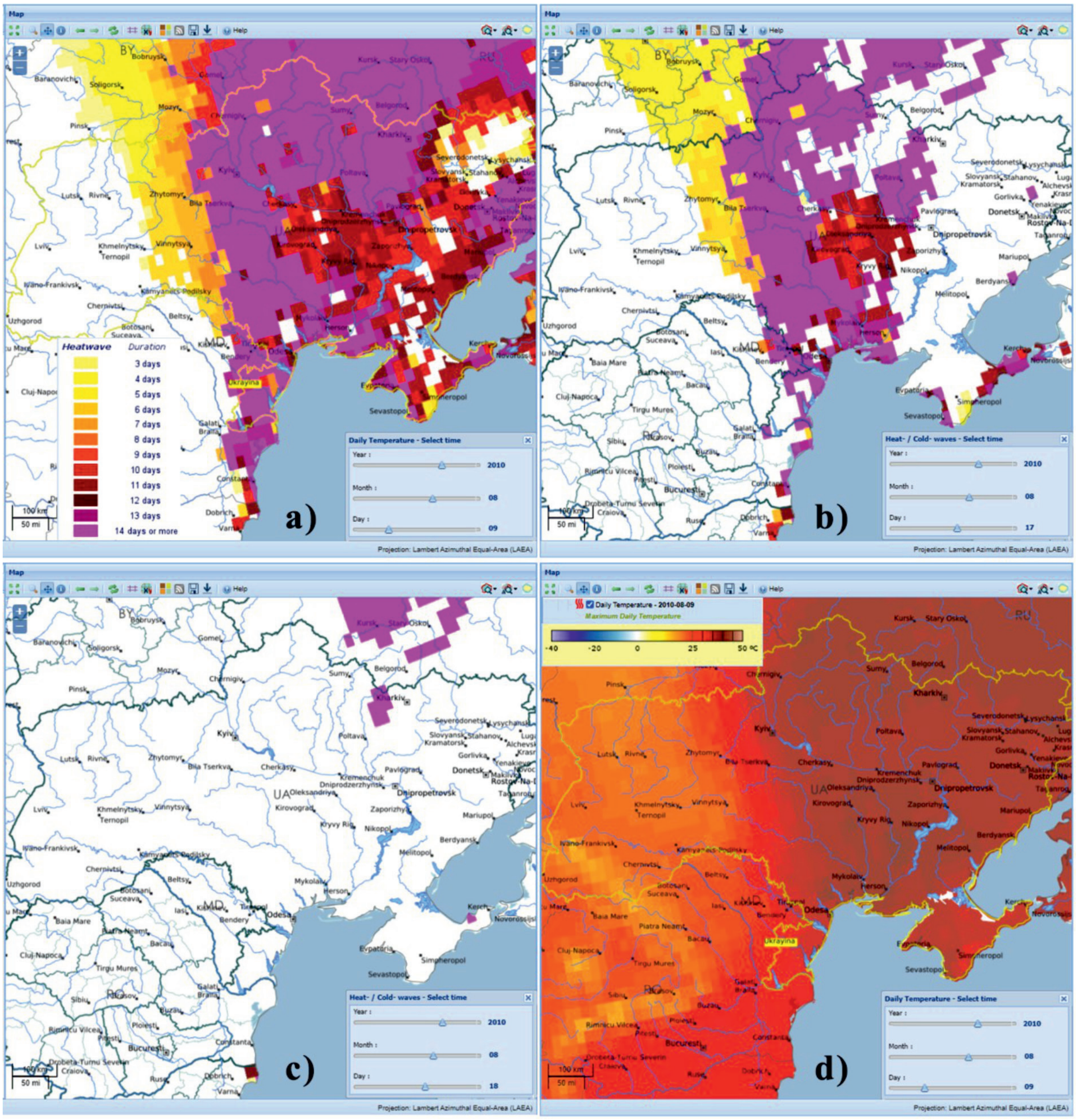

Fig. 5. The extreme heatwave event of 2010 over Ukraine: a) 9.08.2010, b) 17.08.2010, c) 18.08.2010, d) maximum daily temperature of 9.08.2010 (Source: EDO Database).

an adaptation to heat stress is planning. HW it's a phenomenon that in contrast to rain or storms is a creeping disaster that becomes worse when heat is continuing to persist. Therefore, building up archives of meteorology data is needed. Regarding the HW, data processing is every day by EDO on data arriving 2 days after event occurred. These data become available with slight delays (up to 3 days) with respect to the current day.

But how close is the data from EDO to the data about heatwaves obtained from the local weather stations? In order to answer this question, we analyzed the recent studies of HWs carried out in Ukraine. Namely, the work of S. Snizhko concerning HWs that took place in central Ukraine [28], the study by G. Svintsitska characterizing HWs in Odessa [12], a similar work about HWs in Lviv [30], as well as another article by Shevchenko et al. [27], which, among other things, provides data on the intensity of HWs in Ukraine and we can compared all of this with the data obtained from EDO.

It should be noted that the comparison encounters some difficulties. First of all, in most works, the authors used the TXA5 method to determine of HWs. Moreover, the baseline period 1961-1990 is used for its calculation, but not 1981-2010, as it is when calculating HCWI. O. Shevchenko et al. [27], just like ours, the TX90p method and the same reference period 1981-2010 are used, however, the size of the moving window (31-day window) is not the same as in EDO (moving 11-day window).

In the first paper [11], the authors describe the well-known HW that took place in Ukraine in the first and second decades of August 2010. They determine the duration of it at 18-24 days with a maximum on August 8, when the highest temperatures were recorded in Dnipro (+40.9ºC), Kriviy Rih (+39.6ºC), Lubny (+39.5ºC), Kropyvnytskyi and Poltava (+39.4ºC), Cherkasy (+38.1ºC). The map obtained by calculating HCWI (Fig. 5) correctly and clearly demonstrates this HW, indicating its duration as of August 8 from 7 to 14 or more days (for the indicated stations).

Further, the authors confidently say that this HW ended on August 17-18 almost simultaneously at all stations. The HCWI calculations are in complete agreement with this. The values of the maximum air temperature are also confirmed by data from the EDO database.

In this article [11] the authors also talk about a less intense HW detected on Mohyliv-Podilsky weather station from July 16 to July 25, 2007. This event was also confirmed by the map of HCWI from EDO.

Next, we compared the HWs established by G. Svintitska based on observations at Odessa weather station, and reflections of these events on EDO cartographic materials. According to G. Svintsitskaya, there are 14 HWs were recorded for 1998-2017 in Odessa [12]. Most of them are also determined by the HCWI index. Only two HWs, having the lowest intensity – first of two was June 31 – August 5, 2014 and second wave during July 14-19, 2014 with cumulative Tmax 6.4 and 7.2ºC, respectively, turned out to be outside EDO attention zone.

Comparison of HCWI calculations with data on HWs in Lviv [30] did not give as unambiguous results as in the previous two comparisons. Here is what the heatwave's situation detected by HCWI looks like on the calendar dates given in this article (Fig. 6).

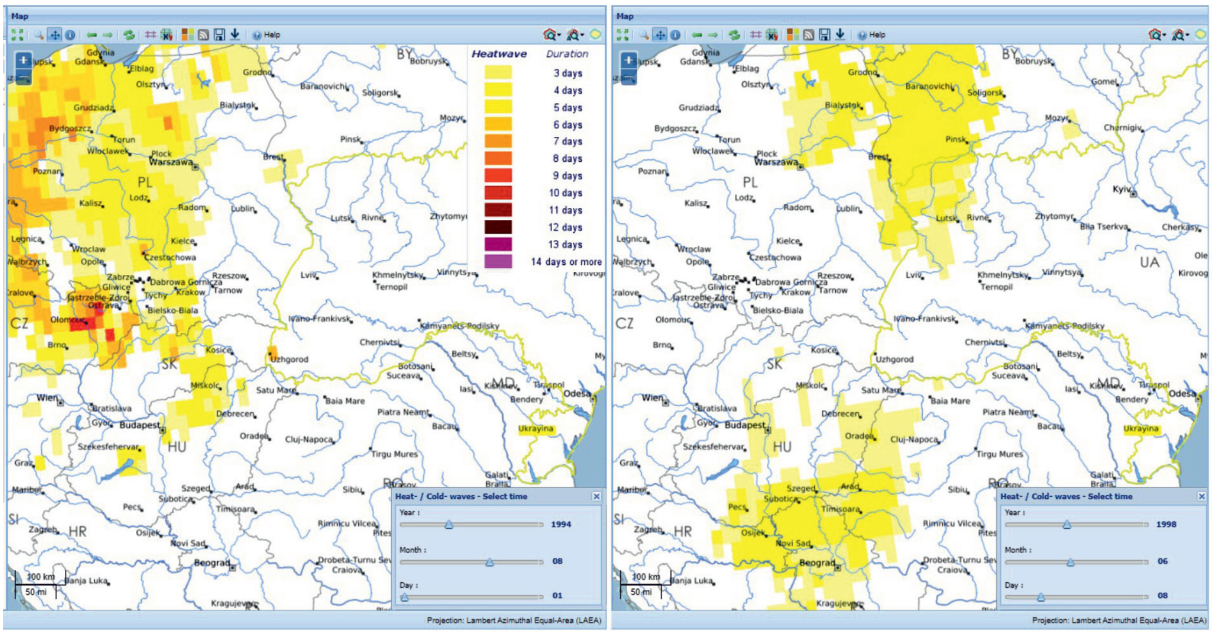

Fig. 6. Image of a heatwave over Ukraine during the detection of the heatwaves at Lviv weather station: a) 1.08.1994, b) 8.06.1998 (Source: EDO Database).

As can be seen from Fig. 6, it cannot be said that HWs were detected in Lviv, although their location is identified not very far. Most likely, this is due to the fact that in above mentioned article analyzes data exclusively from the weather station, but the calculation of HCWI is made by interpolated on a 25x25 km grid, which may include adjacent foothill and mountain areas, where it is cooler; this is seen in Fig. 6. At the same time, the HW in Uzhgorod is clearly visible (Fig. 6a), which, as of August 1, 1994, had already lasted for 1 week. This wave, as the hottest itself and the longest (22.07-9.08) for Uzhgorod, is also mentioned in the work by [9].

Finally, the intensity of HWs calculated by [27] as the average maximum temperature of the HWs are consistent with the temperature extremes values that can be obtained through the "Trend Viewer" of the EDO module (see also Figs 5, 6).

Conclusions

Heatwaves that arose in Ukraine during the period 1981-2021 was detected using the HCWI. According to EDO Database, there are 83 HW events were detected in Ukraine during 1980-2021 (on the average 2 events per year). At the same time, the uneven manifestation of this atmospheric phenomenon in time is clearly traced with the allocation of two half-periods, the duration of which is 21 years. For the first half-period (1980-2000) 29 events of HW were recorded, and for second half-period (2001-2021) − already 54 cases. It should be noted that 1-2 events of HWs were usually recorded in Ukraine per year until 2001, but in the second half-period their frequency increased to 2-3 events, and in some years reached to 4-5 events per year. Analysis of linear trends indicates that in the next 20 years 4-5 HW will already be common.

For each year the frequency, duration and intensity of HWs were analyzed. The maximum length of HW over Ukraine for the study period 1980-2021 ranged from 4 (1984) to 20 (2010 and 2013) days. So, the average duration is 4.2 days, and the average maximum length of HW is 9.45 days. The results of the study show that all indicators characterizing the duration of HW increased during study period. If for 1980-2000 the average duration of the heatwaves was 3.8 days, then for 2001-2021 the average duration increased to 4.3 days. The average maximum length of HW increased more significantly − from 7.4 to 11.5 days in the second half-period. For the next decade, we foresee an increase of the average maximum length of HW to 13.5 days.

The intensity of HWs was evaluated by temperature extreme. The average maximal temperature (1980-2021) during the HW over Ukraine is 32.2ºC. We expect this indicator to increase to 0.5ºC after the next 10 years. The hottest HW event for the study period had maximum daily temperature of 41.4ºC (2010).

It was found that for Ukraine all indicators of HWs were increased during the study period. Growing tendencies of all aspects of the HWs is clearly visible by linear trends, confirming global warming tendencies.

High air temperatures during the HW are damaging to human health, and impacts workplace performance and productivity and as such are important for many aspects of human life. Such conditions may lead to stress thermal load, which cannot be relieved even by means of complete hygienic and town-planning measures. During the HW, it is more difficult for the human body to cool down, especially for elderly or sick people. Hot and humid heat episodes can be deadly, associated with elevated hospital intake. Extreme heat also exacerbates some nosologies, such as asthma, respiratory difficulties, and response to airborne allergens; we observed it in some regions of Ukraine [31]. An increase of HW frequency and duration influences energy sector is affected because a higher electricity demand during summer due to increased use of air conditioning. In most of the territory of Ukraine it will have negative consequences of HW for agriculture, especially in the south of the country. Periods of prolonged heat will provoke soil desiccation and land degradation, reducing crop yields.

We were able to compare the calendar dates, duration and, to some extent, temperature indicators of those HWs that are indicated in the articles under analyze, and detected by HCWI. In most cases, we got a fairly good match. This suggests that HCWI from EDO is a fairly reliable tool for HW analysis. The HCWI indicator that is implemented in EDO is updated on a daily basis (with a two-day delay), and provides a conceptually simple and easy-to-use method for assessing the duration and geographical distribution of heatwaves) over Ukraine, for any given day from 1980 onwards. Furthermore, because it uses both minimum and maximum daily temperatures (Tmin and Tmax), the HCWI indicator takes account of the strong human impacts of nighttime temperatures (i.e. Tmin) during a heatwave, as recommended by WMO.

This contrasts with commonly used methods for measuring heat waves, which only use Tmax. Respectively HCWI can also be applied to study climate changes, determine the period of droughts, the adaptation of population to heat stress and the healthcare system to its consequences. The obtained result will benefit governmental planning studies in a broad range of society comprising health care, transportation, mitigation strategies, emergency services, energy and agriculture.

Conflict of Interest

The authors declare no conflict of interest.

References

1. HEATWAVES AND HEALTH: Guidance on Warning-System Development. Ed by G.R. McGregor, P. Bessemoulin, K. Ebi, B. Menne. Geneva. World Meteorological Organization, 96, **2015**.
2. McCARTHY M., ARMSTRONG L., ARMSTRONG N. A new heatwave definition for the UK. Weather. **74**, 382, **2019**.
3. HEAT WAVE. AMS Glossary of Meteorology. Available online: https://glossary.ametsoc.org/wiki/Heat_wave (accessed on 3 November **2022**).
4. WARD R. The Climates of the United States. American Meteorological Society, USA, pp. 383-395. **1925.**
5. KYSELÝ J. Recent severe heat waves in central Europe: how to view them in a long-term prospect? Int. J. Climatol. **30**, 89, **2010**.
6. HITTEGOLF. The Royal Netherlands Meteorological Institute. Available online: https://www.knmi.nl/kennis-en-datacentrum/uitleg/hittegolf (accessed on 3 November **2022**) [In Dutch].
7. DANMARK FÅR VARME- OG HEDEBØLGE. Danish Meteorological Institute. Available online: https://web.archive.org/web/20080723170544/http://www.dmi.dk/dmi/danmark_faar_varme-_og_hedeboelge (accessed on 3 November **2022**) [In Danish].
8. MALCHEVA K., BOCHEVA L., CHERVENKOV H. Spatio-Temporal Variation of Extreme Heat Events in Southeastern Europe. Atmosphere. **13**, 1186, **2022**.
9. SHEVCHENKO O. Characteristic of heat wave of summer period of 2010 on the territory of Ukraine. Scientific works of UkrNIHMI. **262**, 59, **2012** [In Ukrainian].
10. SHEVCHENKO O., LEE H., SNIZHKO S. MAYER H. Long-term analysis of heat waves in Ukraine. Int. J. Climatol. **34**, 1642, **2014**.
11. SNIZHKO S., SHEVCHENKO O., SVINTSITSKA H. Heat waves in central regions of Ukraine under the conditions of climate change. Bul. Taras Shevchenko National Univ. of Kyiv. Military-special sci. **2** (39), 58, **2019** [In Ukrainian].
12. SVINTSITSKA H.I. Characteristic of heat wave of summer period in Odesa. Geography and tourism, **40**, 176, **2017** [In Ukrainian].
13. 1DIMITRIADOU L., NASTOS P., ZEREFOS C. Defining Heatwaves with Respect to Human Biometeorology. The Case of Attica Region, Greece. Atmosphere, **12**, 1100, **2021**.
14. SULIKOWSKA A., WYPYCH A. Summer temperature extremes in Europe: how does the definition affect the results? Theor. Appl. Climatol. **141**, 19, **2020**.
15. KATAVOUTAS G., FOUNDA D. Response of Urban Heat Stress to Heat Waves in Athens (1960-2017). Atmosphere, **10**, 483, **2019**.
16. SULIKOWSKA A., WALAWENDER J.P., WALAWENDER E. Temperature extremes in Alaska: temporal variability and circulation background. Theor. Appl. Climatol. **136**, 955, **2019**.
17. REZAIE F., AHMADI M., SHAKIBA A. Determining the temperature threshold of the heat wave during the warm period of the year based on Global Index in different regions of the country. J. Geogr. Env. Hazar. **7**, (2), 115, **2018**.
18. REN F., TREWIN B., BRUNET M., DUSHMANTA P., WALTER A., BADDOUR O., KORBER M. A research progress review on regional extreme events. Advances in Clim. Change Research. **9**, 3, 161, **2018**.
19. FENNER D., HOLTMANN A., KRUG A., SCHERER D. Heat waves in Berlin and Potsdam, Germany – Long-term trends and comparison of heat wave definitions from 1893 to 2017. Int. J. Climatol. **39**, 2422, **2019**.
20. FAYE M., DÈME A., DIONGUE A.K, DIOUF I. Impact of different heat wave definitions on daily mortality in Bandafassi, Senegal. PLoS ONE. **16**, (4), e0249199, **2021**.
21. PITICAR A., CROITORU A.-E., CIUPERTEA F.-A., HARPA, G.-V. Recent changes in heat waves and cold waves detected based on excess heat factor and excess cold factor in Romania. Int. J. Climatol. **38**, 1777, **2018**.
22. DE BOECK H.J., DREESEN F.E., JANSSENS I.A. AND NIJS I. Climatic characteristics of heat waves and their simulation in plant experiments. Global Change Biol. **16**, 1992, **2010**.
23. MANDAL R., JOSEPH S., SAHAI A.K., PHANI R., DEY A., CHATTOPADHYAY R. Real time extended range prediction of heat waves over India. Sci Rep. **9**, 9008, **2019**.
24. RUSSO S., SILLMANN J., FISCHER E. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ. Res. Lett. **10**, 124003, **2015**.
25. LAVAYSSE C., CAMMALLERI C., DOSIO A., VAN DER SCHRIER G., TORETI A., VOGT J. Towards a monitoring system of temperature extremes in Europe. Nat. Hazards and Earth Syst. Sci. **18**, 91-104, **2018**.
26. MEQUE A., PINTO I., MAÚRE G., BELEZA A. Understanding the variability of heatwave characteristics in southern Africa. Weather and Climate Extremes, **38**, 100498, **2022**.
27. SHEVCHENKO O., OLIINYK R., SNIZHKO S., SVINTSITSKA H., KOSTYRKO I. Indexing of Heatwaves in Ukraine. Water. **12** (4), 962, **2020**.
28. YIN C., YANG Y., CHEN X., YUE X., LIU Y., XIN Y. Changes in global heat waves and its socioeconomic exposure in a warmer future. Clim. Risk Manag. **38**, 100459, **2022**.
29. SOFTWARE TOOLS. MARS Crop Yield Forecasting System. Available online: https://marswiki.jrc.ec.europa.eu/agri4castwiki/index.php/Software_Tools (accessed on 3 November **2022**).
30. SHEVCHENKO O., SNIZHKO S., MATVIIENKO M. Thermal comfort conditions during heat wave events in Lviv. Constructive Geogr. and Rational Use of Nat. Resour. **1**, 15, **2021** [In Ukrainian].
31. KORNUS A. O., KORNUS O. H., SHYSHCHUK V. D., POTSELUEV V. I. The regional nosogeographical analysis and factors affecting population respiratory morbidity (on example of the Sumy region, Ukraine). J. Geol., Geogr., Geoecol. **29** (1), 82, 2020.