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THE PROJECTIONS OF HEAT WAVE CASES IN UKRAINE IN THE 21ST CENTURY

(Представлено членом редакційної колегії д-ром геол. наук, проф. Д. О. Ляшенком)

Background. ***Heat waves (HW) are well known for their negative impact on human health. HWs can also lead to droughts, forest fires, reduced or lost crops, significant stress on energy systems, destruction of infrastructure facilities and therefore to significant economic losses. According to climate projections, a further increase in air temperature and the frequency of HWs are expected in the coming decades in many parts of the world. This study aims to assess the heat waves that may occur within the territory of Ukraine through the 21st century in terms of number, duration, and intensity based on RCP scenarios.***

Methods. ***A 90th percentile threshold approach was used to determine HW, and HW intensity was assessed using the daily heat wave magnitude index (HWMId). The analysis was conducted using a high-resolution regional climate model from the EURO-CORDEX system (the grid resolution of the used simulation is 0.22 degrees) under scenarios RCP2.6 and RCP8.5.***

Results. ***The results of the study indicate that the frequency of HWs will increase significantly in Ukraine under the high emissions scenario RCP8.5. The number of HWs is expected to more than double by the middle of the 21st century and to increase more than 2.5 times by 2071–2099 compared to the reference period. The duration of HWs will also increase, with the average duration expected to increase by approximately 1.5–2 times by the end of the century compared to the reference period, and the maximum duration by 2–3 times. Under the optimistic RCP2.6 scenario, the frequency and duration of HWs will increase in the near and mid-term future. The rate of increase in the number of HWs under the RCP2.6 scenario will stabilize by the end of the century but the total number of HWs will be higher than in the reference period, duration of HWs will even decrease slightly across almost the entire territory of Ukraine compared to the reference period by the end of the century.***

Conclusions. ***The findings indicate that HW episodes in Ukraine will not only become more frequent in the future, but also longer and more intense, especially if greenhouse gas emissions remain high. The results of this study highlight the urgent need for mitigation and adaptation measures to heat in Ukraine. The projected changes provide a scientific basis for the development and improvement of climate-resilient urban planning, the Heat Health Warning System and adaptation strategies in Ukraine.***

Keywords: ***heat wave, heat wave projections, heat wave magnitude index, Ukraine, climate change.***

Background

According to the WHO (World Health Organization..., 2017), from 2000 to 2016, the number of people affected by abnormal heat increased by about 125 million people. The thermal conditions of the territories deteriorate significantly during the manifestation of heat waves (HW). Extreme HWs were observed in Central Europe in the summer of 1994 (Lhotka, & Kyselý, 2015; Tomczyk, & Bednorz, 2016), June and August of 2003 (Rebetez et al., 2006), in June and July of 2006 (Kyselý, 2010; Monteiro et al., 2013), in the summer of 2015 (Hoy et al., 2017; Krzyżewska & Dyer, 2018) and in July and August of 2010 in Eastern Europe and Western Russia (Grumm, 2011; Shevchenko et al., 2022a). In Ukraine, the most powerful heat waves observed since 1961 are the 2010 heat wave for the northern, central, eastern and southern regions and the 2015 heat wave for the western regions. During these HWs very intensive heat stress prevailed at daytime (Shevchenko et al., 2022a).

Heat waves are well known for their negative impact on the human body (Kovats & Hajat, 2008) and can lead to distinct short-term increases in morbidity and mortality (Basu, 2009; Gosling at al., 2009). According to various sources, the number of human victims from the powerful HW in 2003 is estimated from 20 to 70 thousand people, when the maximum value of HWMId, according to the methodology of Russo, Sillmann, and Fischer (2015), was

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accounted for 44,7. During this HW, extreme weather conditions were observed in Europe – the average summer air temperature in most of the territory of Western and Central Europe exceeded the average values of 1961–1990 by 5 standard deviations, and the summer was probably the warmest since 1540. The mega-heat waves of the summer of 2015 were long and very intense in Europe and caused a lot of extra heat-related deaths in countries where it was observed. During the mega-heat wave of summer 2015, a 14 % mortality increase was found in Slovakia (Výberši et al., 2018). In the Czech Republic, the impact of the mega-heat wave of 2015 on the increase in excess mortality was greater than during the previous very intensive heat wave in 1994 (Urban et al., 2017). Excess mortality was significantly larger among the elderly (65+ years), comparable to mortality within this age group in 1994. In Switzerland, a comparable mortality increases of +5.4 % for the summer of 2015 was noted (Vicedo-Cabrera et al., 2016). An additional mean summer mortality of +5.8 % in the summer of 2015 and daily mortality anomalies of +56 % in July 2015 was found in South-West Germany (Baden–Württemberg) (Muthers, Laschewski, & Matzarakis, 2017).

In addition to the impact on people, heat waves also lead to droughts, forest fires, reduced or lost crops, significant stress on energy systems, destruction of infrastructure facilities and, accordingly, significant economic losses. Data on the most severe droughts in Europe show that some of the most intense drought episodes occur during years with pronounced heat waves (Spinoni et al., 2015), resulting in compounded impacts on society, ecosystems, and the economy. In Europe, total annual losses attributable to heat waves amounted to 0.3–0.5 % of European GDP in 2003, 2010, 2015, and 2018, while the average GDP loss for the period 1981–2010 was about 0.2 % (García-León et al., 2021). In France between 2015 and 2019, the economic impact of some health effects of heat waves amounts to €25.5 billion, it consists mainly of mortality (€23.2 billion), as well as restricted activity days and morbidity (Adélaïde, Chanel, & Pascal, 2022).

Against the background of global climate changes in particular, high temperature weather, such as hot days (denotes very high maximum temperatures), hot nights (which means very high minimum daily temperatures), and heat waves have become more frequent on the global scale (IPCC, 2013). According to climate projections, a further increase in global air temperature is expected in the coming decades. An increase in the frequency of heat waves is also among the most likely manifestations of future climate change. (Huth, Kyselý, & Pokorná, 2000). According to Russo et al. (2014), in the future, the probability of extreme heat waves (like in Central Europe 2003, in Eastern Europe in 2010 and in the USA in 1980) will increase and events considered rare today may be considered the norm under certain future scenarios. Gaitán et al. (2019) have found that according to RCP4.5 and RCP8.5 scenarios during the 21st century heat-wave mean intensity will increase close to 2°C and the duration of HWs will increase by 7 days at the end of the century for Aragón (Spain). Shafiei Shiva, & Chandler (2020) also pointed on increasing in global temperature is driving more frequent and more severe local heat waves within the United States, but mentioned that General circulation models (GCMs) show increasing, but spatially uneven trends in heat wave properties. Gao and Yan (2022) based on the multi-model ensemble of GLMs showed that the heat waves will increase significantly in terms of days, duration and magnitude over China. By the end of the XXI century, the average duration and frequency of heat waves in the three European regions are projected to increase up to 4.5 times from the present-day values and according to the simulations results monotonic increase in severity, duration, and HW days during the twenty-first century (Lau, & Nath, 2014) are found. HW projections, which are based on the RCP scenarios, for two projected thirty-year periods (2021–2050 and 2071–2100) showed that a distinct increase in the number of HWs as well as duration and intensity is expected on the territory of France in the 21st century (Ouzeau et al., 2016).

Research on heat waves for Ukraine has been started relatively recently (Shevchenko et al., 2014; Shevchenko et al., 2020), but they showed an increasing frequency of occurrence of heat waves (HWs) in the territory of Ukraine in the last decades (Shevchenko et al., 2022a). Results of climate simulations for Ukraine project higher air temperature in the 21st century (Krakovska et al., 2021; Krakovska et al., 2018; Snizhko et al., 2020a; Snizhko et al., 2020b) which apparently could lead to more intense, more frequent and longer-lasting heat waves. Research into the projections of HW of Ukraine has been conducted only for a few cities, Kyiv, Odesa, Uzhhorod and Kharkiv (Safranov et al., 2021; Shevchenko et al., 2022b). The HW projections based on RCP scenarios show that an increase in the frequency of this atmospheric phenomenon is expected in Kyiv in the 21st century. Even according to the optimistic RCP 2.6 scenario, an increase in the frequency of HW events in all forecast periods are expected. For the near-term period, the RCP 8.5 scenario is not significantly different from RCP 2.6, however, starting from 2041–2070, all HW indicators for Kyiv increase significantly and the amount of HWs will increase almost four times compared to the historical period by the end of the 21st century (Shevchenko et al., 2022b). The results of the HW projections can be a basis for deeper research into thermal load on people in the future, can be used for the establishment of the Heat Health Warning System (HHWS) of some territories and adaptation plans to climate change, planning of adaptation measures to heat stress during HW cases, etc.

Therefore, this study aims to assess the heat waves that may occur within the territory of Ukraine through the 21st century (in three future time periods: 2011–2040, 2041–2070 and 2071–2099) in terms of number, duration, and intensity based on RCP scenarios.

Methods

A heat wave (HW) is an atmospheric phenomenon that consists of abnormally hot weather that lasts for a certain period and covers large areas. For today, there is no one objective and uniform definition of HW, which creates difficulties in comparing the characteristics of individual cases. All existing definitions of HWs can be divided into several types. There are definitions with a fixed absolute (Gershunov, Cayan, & Iacobellis, 2009; Kyselý, 2002; Russo, Sillmann, & Fischer, 2015) and relative temperature threshold (De Boeck et al., 2010; Kyselý, 2010), as well as definitions that also differ in the duration of the period with temperatures exceeding the limits, after which the hot period is considered to be a heat wave. Definitions with absolute temperature limits are generally used for research in small areas, where the same (or very similar) meteorological conditions are observed. In this research to identify of HW events the following criteria were used: a heat wave is a period of six or more hot days (a hot day is a day with a maximum air temperature above the 90th percentile (derived from the daily maximum temperature values for each station for the reference period 1991–2020 (World Meteorological Organization, 2017).

HW are characterized by duration and intensity. The HW duration is usually calculated either in days of HW manifestation or by specific indexes (for example, Heat Wave Duration Index (HWDI)). When using HWDI, its value is calculated for each year, and then changes in the duration of HW over a certain time period are analyzed (Radinović & Ćurić, 2012).

When it comes to HW intensity, there are various methods for the mathematical representation of this characteristic are used: $T_{\max}$ and $T_{\min}$values, as well as HWWI and HWMId.

The HWMId index, developed by European scientists led by S. Russo, was chosen to assess the intensity of HW (Russo et al., 2014). This index itself is a redevelopment of HWMI (Heat Wave Magnitude Index), which was the first climate indicator merging duration and magnitude of temperature anomalies of heat events into a single number and had some limitations. HWMId is the sum of the magnitudes of consecutive days that form a heat wave, with a daily frequency and is more accurate because its calculation takes into account the intensity of extreme temperatures adapted for use in conditions of global climate change and is useful in the modern classification of HW.

In order to examine the future evolution of heat wave events and their characteristics over Ukraine, the data obtained from the MOHC-HadGEM2-ES simulation belonging to the EURO-CORDEX Project (EURO-CORDEX, 2021; Jacob et al., 2014) was used. The grid resolution of the used simulation is 0.22 degrees (Fig. 1). Points of a regular grid were chosen to create projections of heat waves in Ukraine. For each point, HW events and their duration (in days) and intensity (HWMId) during the warm period (May–September) for the period 1970–2099 were identified. The results of HW projections and their characteristics are presented for three forecast periods: near-term (2011–2040), middle-term (2041–2070), far-term future (2071–2099), and also for the basic (historical) period, 1970–2005.

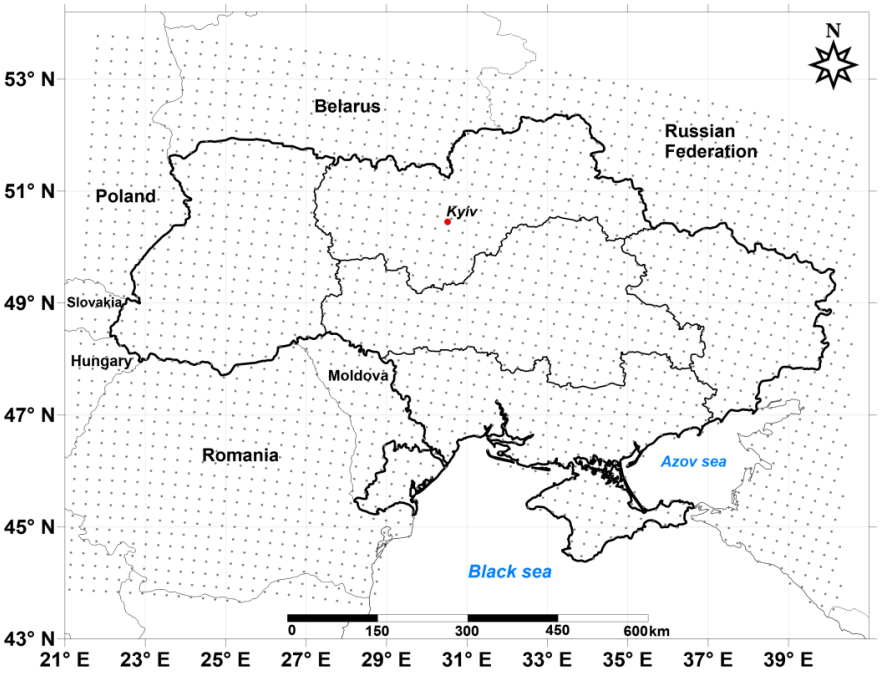


Fig. 1. Distribution of MOHC-HadGEM2-ES simulation points belonging to the EURO-CORDEX Project over the territory of Ukraine

To obtain forecasts of climate evolution, climate models use information described in scenarios of greenhouse gas emissions and emissions of pollutants into the atmosphere or land use models. (Moss et al., 2008). Scenarios are created using a variety of approaches, from simple idealized experiments to integrated evaluation models. The main factors that determine changes in anthropogenic emissions of greenhouse gases are economic and demographic development, lifestyle and changes in behavior, related to changes in energy consumption and land use, technology and climate policy, which are still uncertain. The standard set of scenarios used in the Fifth Assessment Report of the International Panel on Climate Change (AR5) is called Representative Concentration Pathways (RCP) (Moss et al., 2008).

RCPs are four greenhouse gas concentration trajectories adopted in 2014: RCP2.6, RCP4.5, RCP6, and RCP8.5, which are named for the possible magnitude of radiative forcing in 2100 compared to pre-industrial values (+2.6, +4.5, +6.0 and +8.5 W/m^2). The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss et al., 2010).

In this research, to create projections of heat waves in Ukraine until the end of the 21st century, two scenarios, RCP 2.6 and RCP 8.5, were used. Currently, it is this set of scenarios that is actively used for various studies related to the future manifestations of HW (Kishore et al., 2022; Ouzeau et al., 2016), as well as in the modeling of adjacent characteristics that are qualitatively correlated with cases of HW under conditions of global warming.

RCP 2.6 is the most optimistic scenario with the earliest emission peak about 2020, which takes into account measures to avoid global warming. The goal of this scenario is to prevent an increase in global temperature of more than 2°C relative to the pre-industrial level. RCP 2.6 scenario (IPCC, 2014) calls for a reduction in carbon dioxide emissions by 2020 and their complete absence by 2100.

RCP 8.5 is the "worst case" climate change scenario with very high greenhouse gas emissions (IPCC, 2014), based on an overestimate of projected coal production, characterized by an increase in greenhouse gas emissions over time, which is representative of scenarios that lead to high levels of greenhouse gas concentrations.

Results

Number of HW. Starting in 2011–2040, an increase in the frequency of HWs is expected (Fig. 2 a). Under the RCP 2.6 scenario, the highest increase is expected in the southern region of Ukraine. The average number of HW cases per region will be almost 95 cases over a thirty-year period, which is 32 cases more than during the reference period (1991–2020) (Tab. 1). The highest increase in HW occurrence is expected in the coastal areas of the Black and Azov Seas. In the northern region, the number of HW cases will increase slightly – by an average of 6.5 cases compared to the reference period – but the increase will be uneven across the territory. North of Zhytomyr, even a slight decrease in the frequency of heat waves is expected. In the eastern region, the number of HWs is expected to increase by almost 24 cases compared to the reference period, and in the central and western regions by approximately 15 cases. Overall, under the RCP 2.6 scenario, the number of HWs in Ukraine is expected to increase by approximately 30 % between 2011 and 2040. Under the RCP 8.5 scenario, the frequency of HWs is expected to increase by 25–30 cases in the northern, western, and central regions. The eastern region is characterized by an increase in the frequency of HWs by almost 38 cases. For the southern region of Ukraine (as under the RCP2.6 scenario), the largest increase in the frequency of HWs is expected in the first forecast period. On average, the number of HW cases in the region will increase by 50 and reach more than 113 cases. In the coastal areas of the Black and Azov Seas, the increase in the number of HW cases will reach 70–80 cases (Fig. 2 b). In general, under an unfavorable scenario, the number of HW cases in Ukraine is expected to increase by 50 % compared to the reference period.

Between 2041 and 2070, the frequency of heat waves is expected to increase further (Fig. 2 c). Under the RCP 2.6 scenario, the frequency of heat waves in the western, northern, and central regions will increase by approximately 15, 19, and 20 cases, respectively, compared to the reference period. In eastern Ukraine, the number of HWs will be 97 (+30 relative to the reference period), and in the south, almost 102 (+39 relative to the reference period). The period 2041–2070 under a favorable scenario is characterized by an increase in the number of HW by almost 40 % in Ukraine. Under the RCP 8.5 scenario, the number of HW cases increases significantly in the middle-term period. The increase in the number of HW cases rises from the northwest, where the increase is +50–60 HW cases, to the south-southeast, where the increase reaches 100–110 HW cases (Fig. 2d). Under an unfavorable scenario, the number of HW in Ukraine will more than double in the period 2041–2070.

According to the RCP 2.6 scenario, between 2070 and 2099, most of the territory is expected to increase in the frequency of HWs by 2–4 cases compared to the previous period (Fig. 2 e). The only exception is the northern region, where there's been a slight decrease in the number of HW cases compared to the past, and the southern region, where the number of cases increases by 6. According to the RCP8.5 scenario, a significant increase in the frequency of HWs is expected throughout Ukraine in the period 2070–2099. In the northwest, the frequency will increase by 80–100 cases compared to the reference period (Fig. 2 f). The largest increase in the number of HWs will be in the northeast and far east of the country, reaching 120 cases. The coastal part of Ukraine, which in other periods was characterized by an increased number of HWs, has slightly lower values here, reaching about +60 cases. The highest number of HWs will be observed in the eastern region, with more than 178 cases. Overall, under an RCP8.5 scenario, the number of HWs in Ukraine will increase more than 2.5 times in the period 2070–2099.

Table 1

The average number of HW for the regions of Ukraine for different periods

Period	RCP 2.6					RCP 8.5				
	Region					Region				
	Central	*East*	*West*	*North*	*South*	*Central*	*East*	*West*	*North*	*South*
1991–2020	62.9	66.3	64.2	60.3	62.2	62.9	66.3	64.2	60.3	62.2
2011–2040	78.3	90.0	78.6	66.8	94.8	92.5	104.1	92.5	85.0	113.1
2041–2070	83.3	97.0	80.1	79.7	101.6	141.7	150.1	129.8	128.7	154.6
2070–2099	87.1	100.2	81.4	79.1	107.6	165.9	178.3	161.4	162.5	161.0

Average HW duration (AD). It is expected that according to the RCP 2.6 scenario, the average duration of HW in 2011–2040 will not change significantly. Changes in this characteristic will vary within +/-0.5 of the day in almost the whole territory of Ukraine (Fig. 3 a, Tab. 2). The exceptions are the coast of the Black and Azov Seas and the northwestern part of Polissia, where the average duration of HW increases by several days. Under the RCP 8.5 scenario, the AD will increase from west to east/southeast. As can be seen from Fig. 3 b, the maximum characteristic changes are expected in the Carpathian region (downward) and in the Crimea and in the northeastern area of Ukraine (upward). Expected changes in the AD by regions will range from -0.4 of the day in the western region to +0.8 of the day in the eastern region (Tab. 2). The AD in the territory of Ukraine relative to the reference period will decrease by 2.4 % under RCP 2.6 scenario and increase by 2.4 % under RCP 8.5 scenario.

In the period 2041–2070, according to the RCP 2.6 scenario, the AD will increase from the west to the southeast of the country (Fig. 3 c). The smallest characteristic values are expected in the Carpathian region, the largest in the Crimea and the west coast of the Azov Sea (up to +7). By region, the change in the AD relative to the reference period will vary from –0.7 of the day in the western region to +1 day in the eastern (Tab. 2). According to the RCP 8.5 scenario, in the period 2041–2070, an increase in the AD is expected throughout the territory of Ukraine. The characteristic will increase from the northwest to the southeast. The maximum increase in the characteristic is expected up to +16 days on the western coast of the Azov Sea (Fig. 3 d). The increase in the AD relative to the reference period will be in the range of approximately +1.5 days in the western and northern regions to +4.7 days in the southern region. In general, on the territory of Ukraine in the middle-term future, the AD according to the RCP 2.6 scenario will practically not change, and according to the RCP 8.5 scenario it will increase by 30 %.

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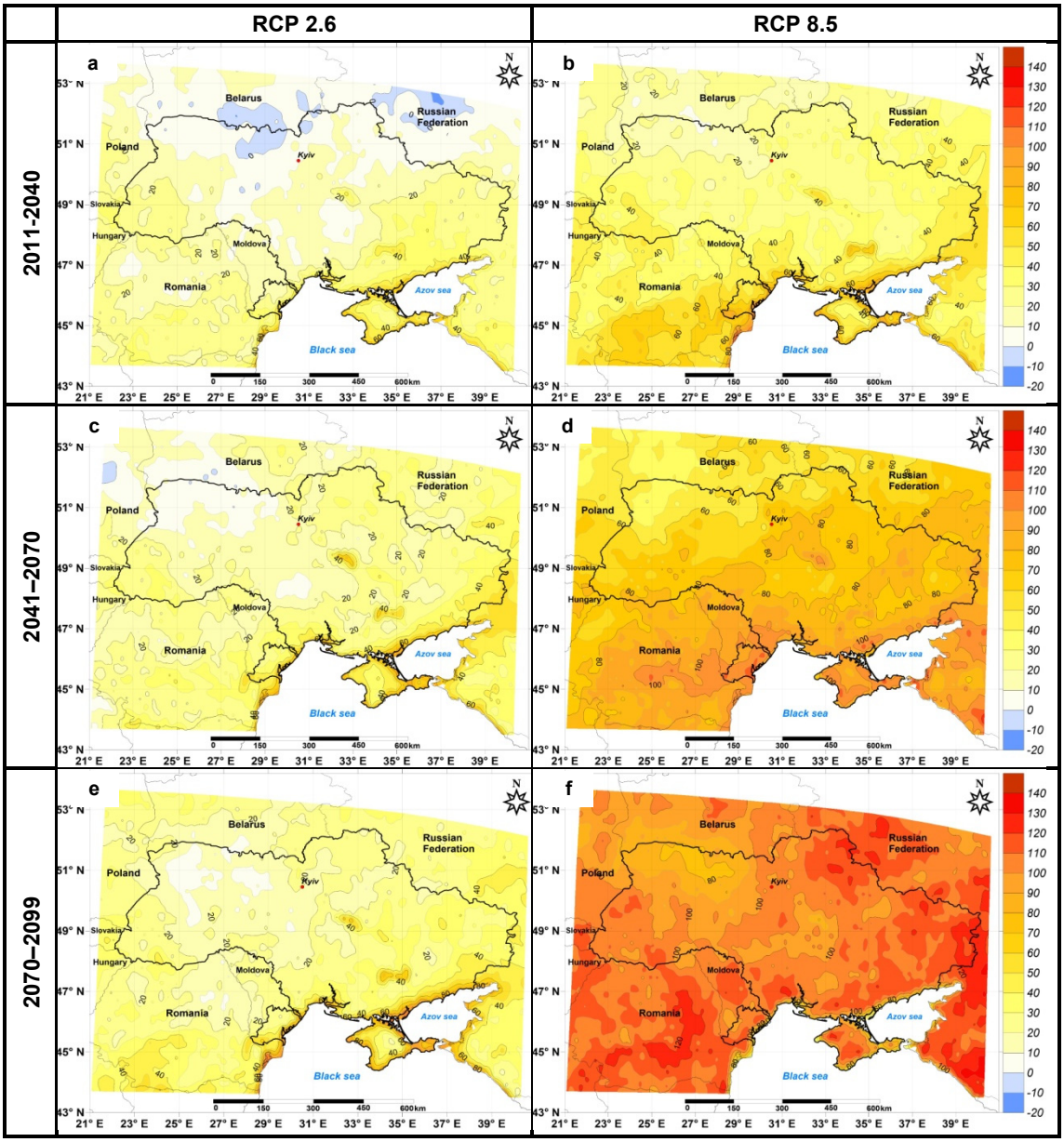


Fig 2. Anomalies of the number of HW compared to the base period and for the periods 2011–2040 (upper row), 2041–2070 (middle row), 2070–2099 (lower row) according to the scenario RCP 2.6 (left column) and RCP 8.5 (right column)

According to the RCP 2.6 scenario in the period 2071–2099, the AD distribution is similar to the near-term future (Fig. 3 e). In the eastern region, the AD will not change relative to the reference one, in the southern region it will increase by 0.4 of the day, in other regions it will decrease by 0.3–0.4 of the day. (Tab. 2). According to the RCP 8.5 scenario, the AD will continue to increase. The AD will increase from west to east and from north to south of Ukraine. In some parts of the coast of the Azov Sea, the greatest growth of the AD will be noted (up to +40–45 days, Fig. 3 f). The increase in the AD by region will range from +4.5 days in the western region to +11.4 days in the southern region (Tab. 2). The AD in the territory of Ukraine in far-term future relative to the reference period far-term future will increase by 75 % under RCP 8.5 scenario and practically will not change under the RCP 2.6 scenario.

Table 2

The average HW duration for the regions of Ukraine for different periods

Period	RCP 2.6					RCP 8.5				
	Region					Region				
	Central	*East*	*West*	*North*	*South*	*Central*	*East*	*West*	*North*	*South*
1991–2020	9.2	8.9	9.3	9.3	9.2	9.2	8.9	9.3	9.3	9.2
2011–2040	8.8	8.5	9.2	9.0	9.2	9.2	9.7	8.9	9.3	9.7
2041–2070	9.1	9.4	8.6	8.9	10.2	11.4	11.8	10.9	10.8	13.8
2070–2099	8.8	8.9	9.0	9.0	9.6	15.2	16.3	13.8	14.0	20.6

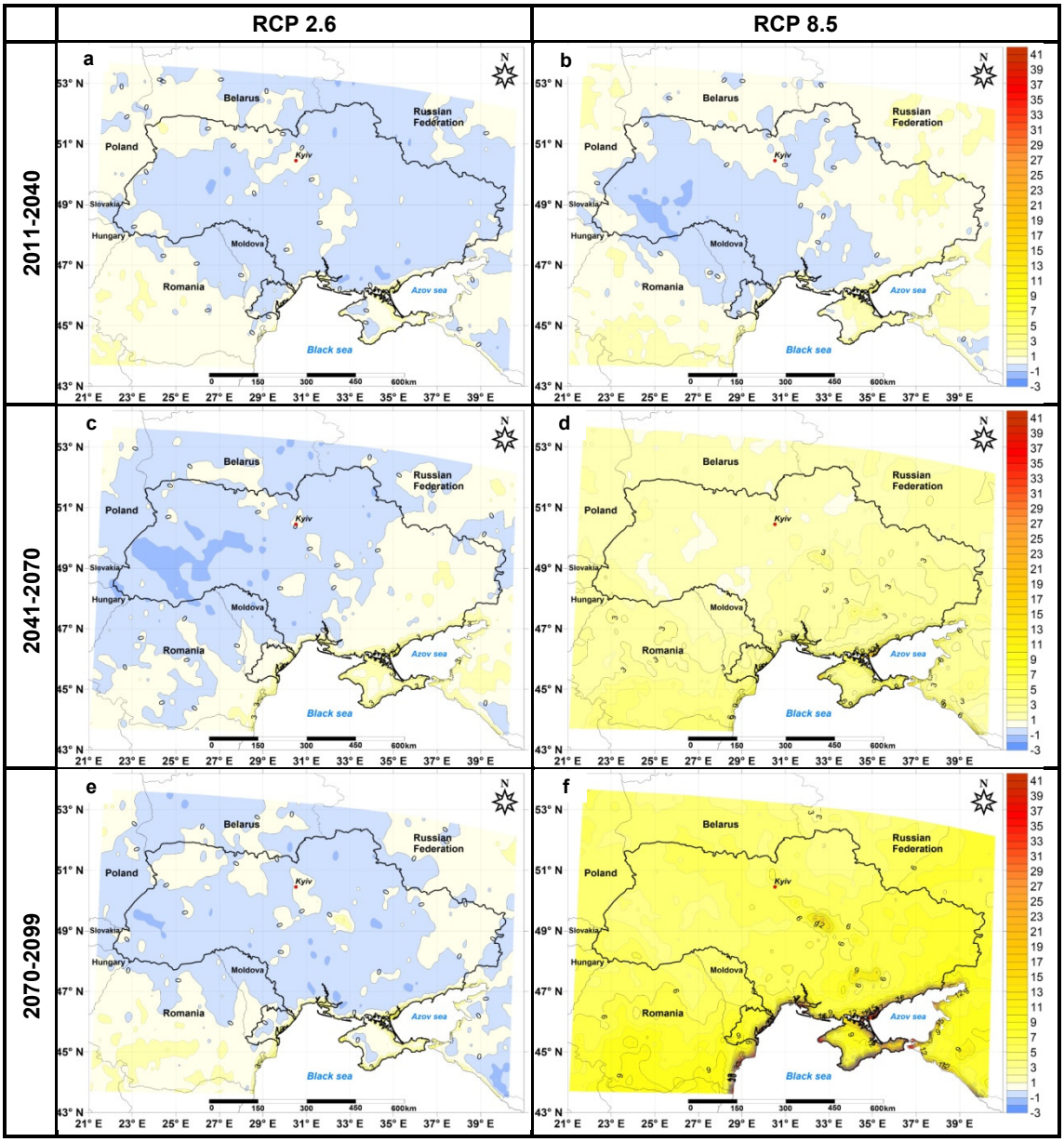


Fig 3. Anomalies of the average HW duration compared to the base period and for the periods 2011–2040 (upper row), 2041–2070 (middle row), 2070–2099 (lower row) according to the scenario RCP 2.6 (left column) and RCP 8.5 (right column)

Maximum HW duration (MD). In the period 2011–2040, according to the RCP 2.6 scenario, the MD is expected to decrease in almost the entire territory of Ukraine. The exception is the coast of the Black and Azov seas, some areas in the central region, Kyiv, the area on west of Ukraine, where the characteristic increases up to +40 days in some points (Fig. 4 a). The greatest decrease in the MD is expected in the square 48°N – 52°N and 25.5°E – 30.5°E and will reach -40 days. By region, the change in MD will range from -13.7 days in the northern region to +3.9 in the southern (Tab. 3). In the period 2011–2040, according to the RCP 8.5 scenario, the area of MD decrease (west and north of Ukraine) and the area of its increase (the rest of the territory) are distinguished (Fig. 4 b). The area of decreasing values of the characteristic coincides with the similar area of the RCP 2.5 scenario. The change in MD by region ranges from -13.3 days in the northern region to +11.9 days in the southern region (Tab. 3). The MD in the near-term future in Ukraine will decrease by 20 % according to the RCP 2.6 scenario and by 4 % according to the RCP 8.5 scenario.

Table 3

The maximum HW duration for regions of Ukraine for different periods

Period	RCP 2.6					RCP 8.5				
	Region					Region				
	Central	*East*	*West*	*North*	*South*	*Central*	*East*	*West*	*North*	*South*
1991–2020	31.1	26.5	31.4	38.7	24.9	31.1	26.5	31.4	38.7	24.9
2011–2040	22.4	20.9	24.2	25.0	28.8	30.9	28.8	24.0	25.5	36.8
2041–2070	32.2	28.7	21.6	25.2	40.5	46.2	59.1	50.0	51.9	69.6
2070–2099	23.3	25.7	24.8	23.4	29.7	67.6	84.8	61.3	57.6	96.7

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The MD distribution in the period 2041–2070 according to the RCP 2.6 scenario is similar to the distribution according to the RCP 8.5 scenario for the near-term future. The areas of decrease and increase of the characteristic almost coincide, however, the maximum values in the middle-term future will increase slightly (Fig. 4 c). The MD by region will range from -13.6 days in the northern region to +15.6 days in the southern (Tab. 3). In the period 2041–2070, according to the RCP 8.5 scenario, a significant increase in the MD is expected in almost the entire territory of Ukraine up to +100 days in certain points of the coastal area of the southern region. The exception is some small areas of the central and part of the northern region of Ukraine, where the MD decreases to -25 days in some points (Fig. 4 d). The MD by region will increase from +13.2 days in the northern region to +44.8 days in the southern (Tab. 3). In the middle-term future in Ukraine, according to the RCP 2.6 scenario, the MD will decrease by 3 %, and according to the RCP 8.5 scenario, it will increase by approximately 80 % relative to the reference period.

In the period 2070–2099, the MD distribution according to the RCP 2.6 scenario is similar to the distribution in the period 2011–2040. However, the growth area of the characteristic in the southern region will increase, and the MD will increase to +65 days in some points (Fig. 4 e). The values of the MD by region in these periods will differ by approximately +/-1–1.5 days (Tab. 3). According to the RCP 8.5 scenario, in the period 2070–2099, the increase in the MD will continue throughout Ukraine (Fig. 4 f). The greatest values of the MD are expected in the coastal areas of the southern region and will reach +120 days in some points, that is, such HWs will begin to appear that can last almost the entire studied period. The MD will increase from +18.9 in the northern region to +71.8 in the southern region (Tab. 3). In the far-term future on the territory of Ukraine, according to the RCP 2.6 scenario, the MD will decrease by 17 %, and according to the RCP 8.5 scenario, it will increase by approximately 140 % relative to the reference period.

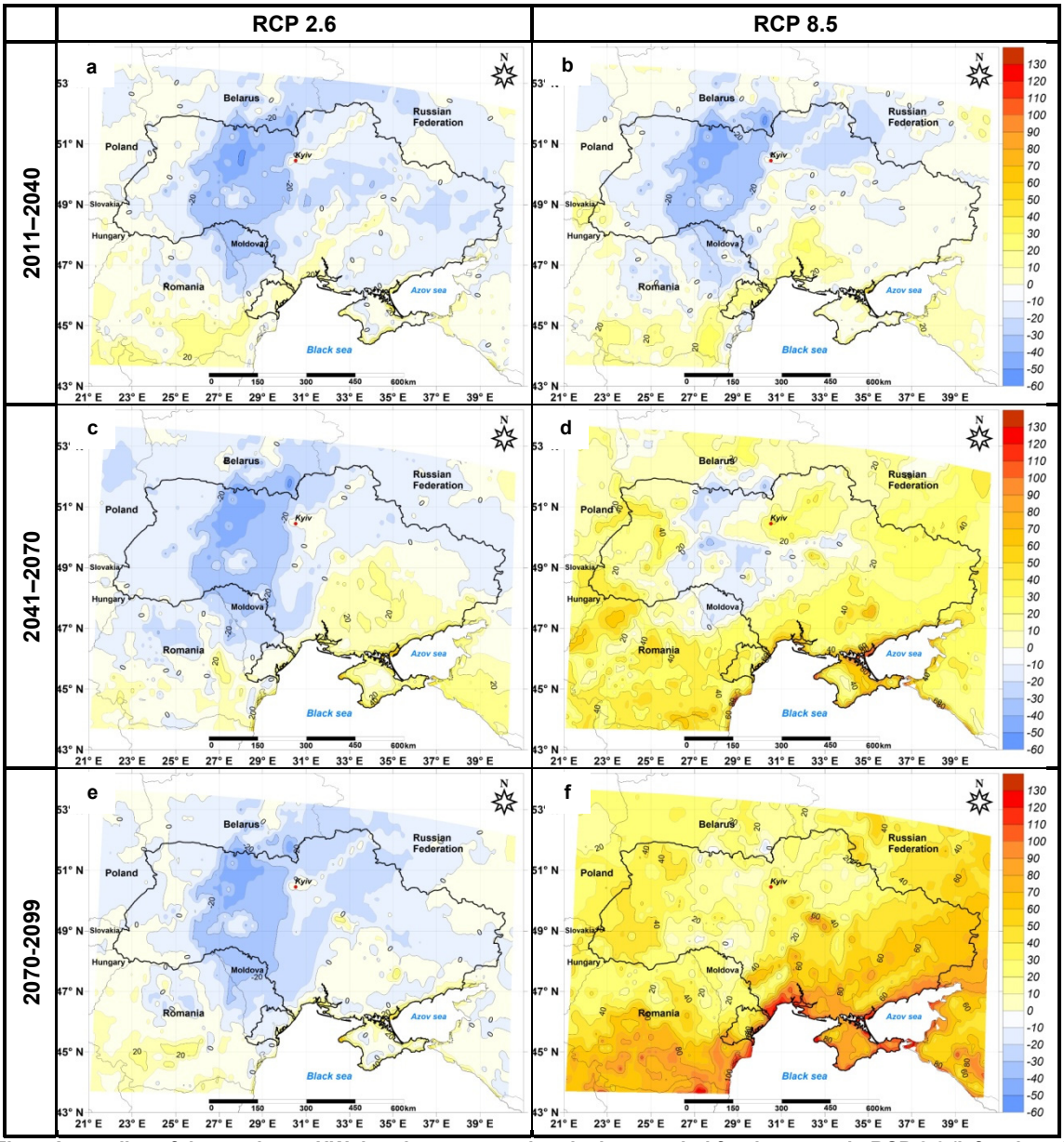


Fig 4. Anomalies of the maximum HW duration compared to the base period for the scenario RCP 2.6 (left column) and RCP 8.5 (right column) and for the periods 2011–2040 (upper row), 2041–2070 (middle row), 2070–2099 (lower row)

Average HWMId of HW. Under the favorable scenario (RCP 2.6), most regions of Ukraine will experience an average decrease in the intensity of HW compared to the reference period (1991–2020) (Tab. 4). The greatest manifestation of this trend is expected in the northeastern and eastern regions, as well as in some central (Vinnytsia, Cherkasy, Poltava) and western (Ternopil, Khmelnytsky) regions (Fig. 5 a). The intensity in the Southern region will increase the most – from 23.3 to 24.4 on average according to the HWMId index (Tab. 4). Also, the average intensity will increase in the Western region from 25 to 25.1 according to the HWMId (Tab. 4). Under the unfavorable scenario (RCP 8.5), the average intensity of heatwaves is expected to increase from 2011–2040 (Fig. 5 b). The highest intensity is expected in the Eastern – 25.8, and Southern – 26.6 regions, which is 3.5 and 3.3 points higher than in the reference period, respectively, according to the HWMId index (Tab. 4). In western Ukraine, the intensity of heatwaves is expected to decrease by an average of 0.8 points, but this decline will be uneven across the territory. In general, under the unfavorable scenario, a significant increase in the average intensity of HW according to HWMId is expected throughout Ukraine.

In the period 2041–2070, according to the RCP 2.6 scenario, an uneven distribution of HW intensity is expected over the territory of Ukraine (Fig. 5c). For the northern and western regions and for some central and southern districts as well, a decrease in the average intensity of HW is expected. The greatest decline will be observed in the northern regions, where the intensity will decrease by an average of 2.6 indicators according to HWMId (Table 4), and for the western region – by 1.1. In the southern and eastern regions, the intensity will increase significantly compared to the reference period. For the southern region, the index will be 28.4 (+5.1 relative to the reference), for the eastern region – 24.8 (+2.5 relative to the reference) (Tab. 4). According to the RCP 8.5 scenario, HW intensities increase from the northwest, where the increase is +8–9 indicators according to HWMId, to the south-southeast, where the value of the increase reaches from 35.2 to 45.3 indicators (Fig. 5 d). In the central and eastern regions, the index will be 35.2 and 36.1, which is 11.6 and 13.8 more than the reference period. Under an unfavorable scenario in the period 2041–2070, the average intensity of HW on the territory of Ukraine will increase by an average of 36 %.

In the period 2070–2099, the intensity of the phenomena will decrease on the whole territory of Ukraine, except for some "heat islands" where this characteristic will slightly increase (Fig. 5 e). In the period 2070–2099, in the northern, central and western regions, the intensity of the HW will decrease to 22.8 in the north (-0.6 relative to the reference), 22.7 in the center (-0.9 relative to the reference) and 24 in the west (-1 relative to the reference). A slight increase in intensity is also expected in the agglomerations of large cities. In general, under the unfavorable scenario, in the period 2070–2099, the average HW intensity in Ukraine will increase by more than 58 % compared to the reference period (Fig. 5 f). In the northwest, where intensity changes are minimal under the favorable scenario, the capacity will increase by 20–21 HWMId indicators compared to the reference period. The calculated values of the index in the northern and western regions are almost identical and amount to 43.6 and 46.1, respectively. In the central and eastern parts of Ukraine, intensity increases are also expected to be quite significant: +27.9 for the central region and +34.6 for the eastern region. The highest average HW intensity will be observed in the southern region, with an index of 80.2 (+56.9 relative to the reference).

Maximum HWMId of HW. The expected values of the maximum intensity of HW (according to HWMId) vary by region: they increase from north to south and from west to east. According to the favorable scenario (RCP 2.6), in the period 2011–2040, the decrease will be observed in the eastern, central, western and northern regions of the country, but will be uneven (Fig. 6 a). The largest decline is expected in the north, where the index value will be 67.2, which is 70 points lower than in the period 1991–2020. In the southern part of the country (especially in the coastal areas of the Black and Azov Seas), the maximum intensity of the heatwave will increase compared to the reference period, with an increase in the index value by 20 points. Under the unfavorable scenario (RCP 8.5), the maximum intensity in the period 2011–2040 will be much lower in the west and north of the country (Fig. 6 b) and will differ from the reference period by 50–60 points. In the central and eastern regions, more intense heatwaves are expected, with maximum index values of 88.8 and 85.3. The highest maximum values of the heatwave intensity are expected in the southern region of Ukraine (as in the RCP2.6 scenario). On average in the region, the intensity of the HW will increase by 58 % compared to the reference period (1991–2020) (Tab. 5), and the maximum value of the index will be 113.5.

The period 2041–2070 under the favorable scenario is characterized by a further decrease in the maximum intensity for most areas, but an increase in the maximum intensity of the heatwave in the south, especially on the coasts of the Black and Azov Seas (Fig. 6 c). Under the RCP 8.5 scenario, the maximum heatwave intensity increases from the northwest to the south-southeast. In the northern and western regions, the maximum intensity is expected to increase by about 66 and 91 values, respectively, in the central region – by 78 values, with an average maximum intensity of 183. In the south and east, the most intense HWs are expected to occur, with HWMId scores of 279 and 229 (Fig. 6d), which is almost twice as high as in the reference period (1991–2020).

Table 4

Average values of HW intensity (by index) for the regions of Ukraine for the periods

Period	RCP 2.6					RCP 8.5				
	Region					Region				
	Central	*East*	*West*	*North*	*South*	*Central*	*East*	*West*	*North*	*South*
1991–2020	23.6	22.3	25.0	23.4	23.3	23.6	22.3	25.0	23.4	23.3
2011–2040	23.0	21.5	25.1	22.7	24.4	24.3	25.8	24.2	24.2	26.6
2041–2070	24.0	24.8	22.4	22.3	28.4	35.2	36.1	34.1	31.5	45.3
2070–2099	22.7	22.6	24.0	22.8	24.8	51.5	56.9	46.1	43.6	80.2

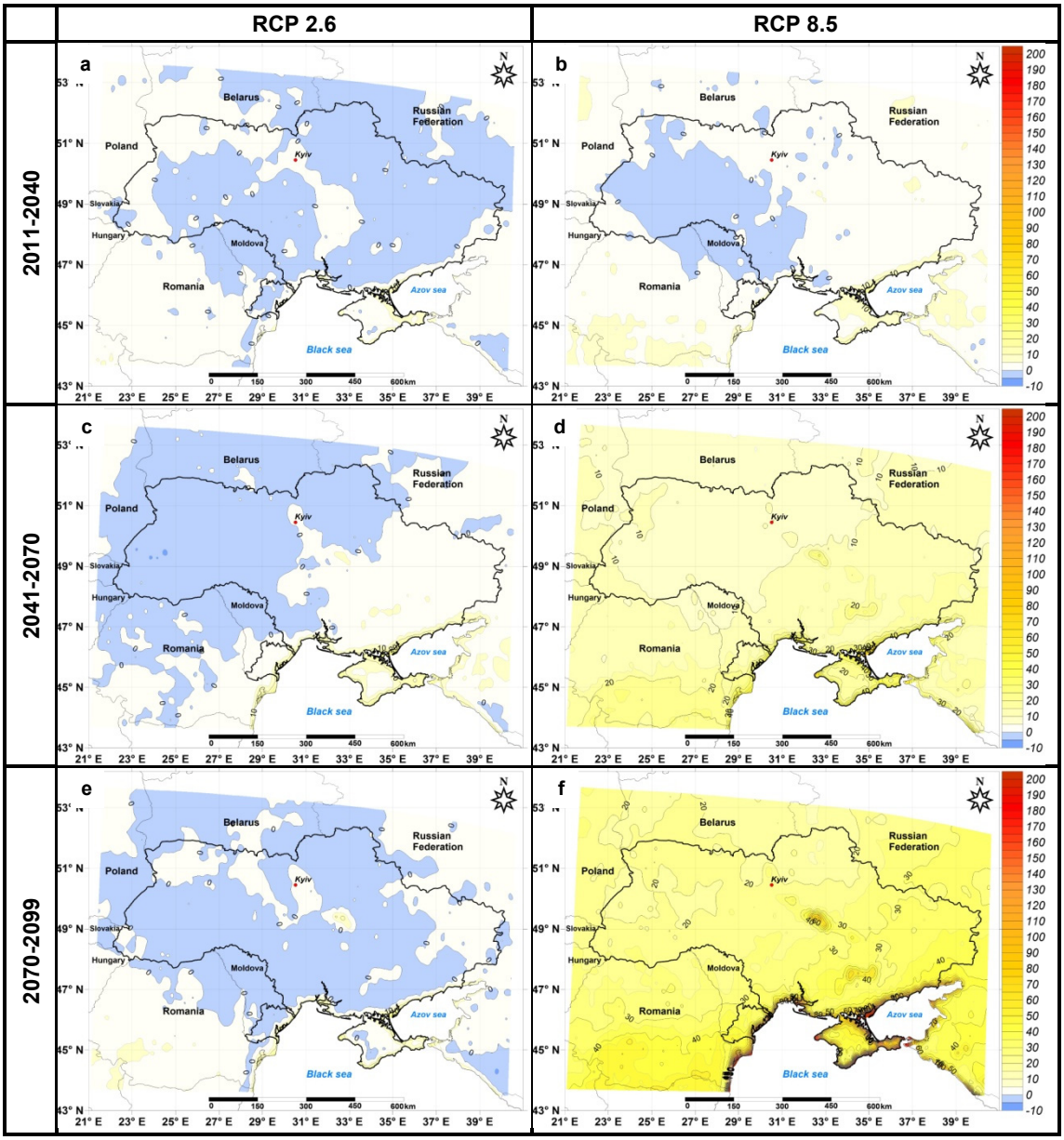


Fig. 5. Anomalies of the average HW intensity compared to the base period and for the periods 2011–2040 (upper row), 2041–2070 (middle row), 2070–2099 (lower row) according to the scenario RCP 2.6 (left column) and RCP 8.5 (right column)

Table 5

Maximum values of HW intensity (by index) for the regions of Ukraine for the periods

Period	RCP 2.6					RCP 8.5				
	Region					Region				
	Central	*East*	*West*	*North*	*South*	*Central*	*East*	*West*	*North*	*South*
1991–2020	104.2	95.9	121.4	137.5	71.6	104.2	95.9	121.4	137.5	71.6
2011–2040	68.8	58.8	73.2	67.2	91.8	88.8	85.3	70.3	77.4	113.5
2041–2070	96.4	81.1	59.8	74.5	132.1	182.8	229.5	212.3	203.4	279.5
2070–2099	64.7	65.5	81.9	66.4	88.8	257.8	377.0	230.9	202.6	417,9

Under the favorable RCP 2.6 scenario, the distribution of the maximum intensity of the heat wave continues to decrease in the period 2070–2099 (Fig. 6e). In the north of Ukraine, the largest decrease in the maximum intensity of the heat wave is expected – by 73 indicators, while in the western, central and eastern regions the maximum intensity will be 81.9, 64.4 and 65.5. The exception is the southern part of Ukraine, where the maximum intensity is estimated at almost 89, which is lower than in the mid-term period, but 17 indicators higher than in the reference period (Tab. 5). Under the RCP8.5 scenario, the maximum intensity of heatwaves continues to increase throughout Ukraine in the period 2070–2099 (Fig. 6f). In the north and west, the increase in the maximum intensity was 65 and 109 indicators, respectively. In the area between the 26th and 30th meridian, the lowest values are expected in this period. Under the unfavorable scenario, in the period 2070–2099, the maximum intensity of HW throughout Ukraine will increase by an average of 2.5 times compared to the reference period: in the central region – 257.8, in the eastern region – 377. The highest values of the HWMId index will be observed in the south and will amount to 417.9, which is four times higher than the maximum intensity in the period 1991–2020.

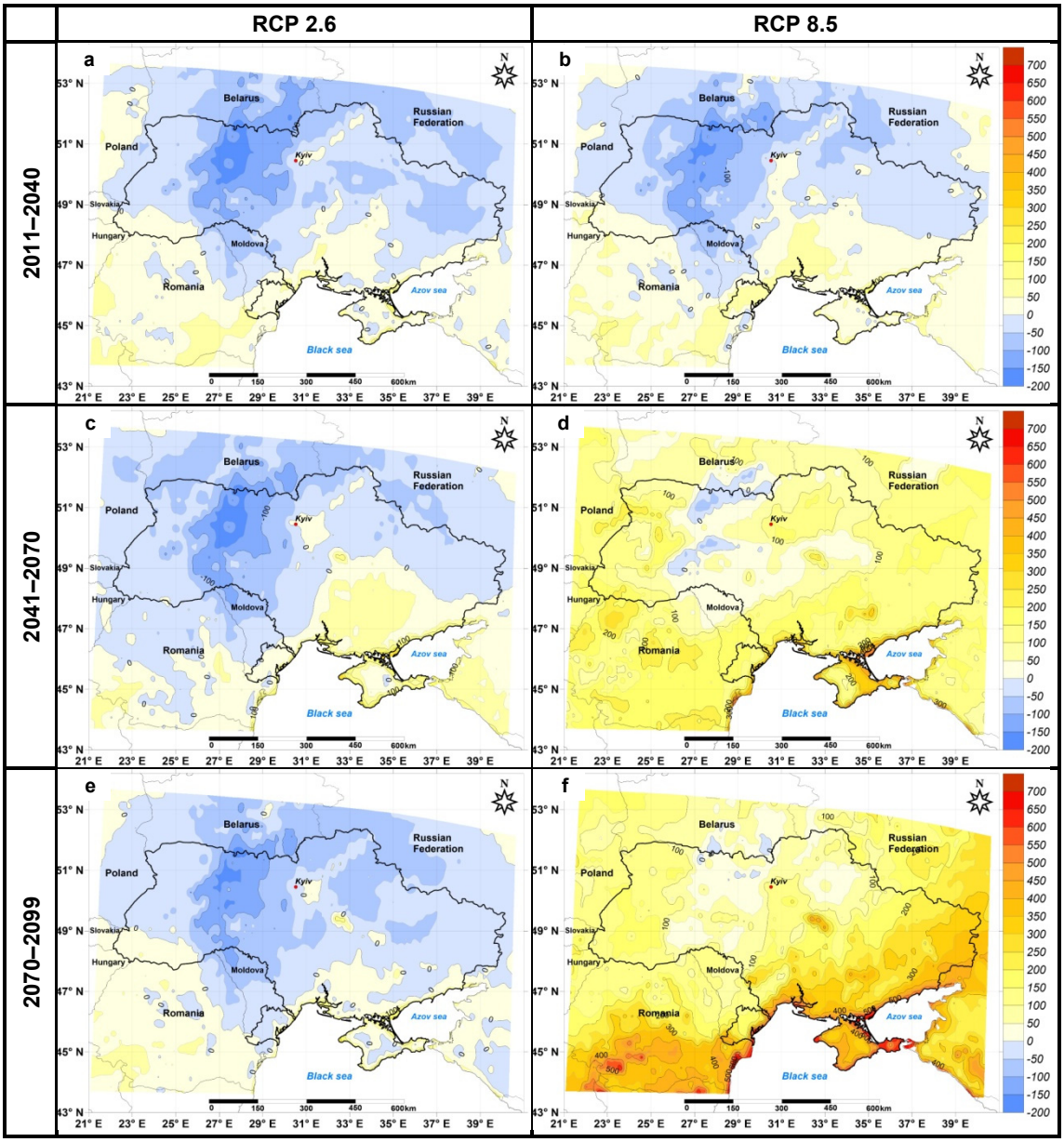


Fig. 6. Anomalies of the maximum HW intensity compared to the base period for the scenario RCP 2.6 (left column) and RCP 8.5 (right column) and for the periods 2011–2040 (upper row), 2041–2070 (middle row), 2070–2099 (lower row)

Discussion and conclusions

This study provides a comprehensive assessment of the projected changes in heat wave characteristics in Ukraine during the 21st century. The analysis was conducted using a high-resolution regional climate model from the EURO-CORDEX system under scenarios RCP2.6 and RCP8.5. The analysis was based on an assessment of the number, duration and intensity of heat waves and their changes over the forecast 30-year periods (the near future 2011–2040, the middle-term future 2041–2070 and the long-term future 2070–2099) compared to the reference period 1991–2020. A 90th percentile threshold approach was used to determine HW, and HW intensity was assessed using the daily heat wave magnitude index (HWMId). This allowed for a reliable comparison between regions and time periods.

The results of the study clearly indicate that the frequency of HWs will increase significantly in Ukraine, and under the high emissions scenario RCP8.5, HWs could become a serious climate risk for Ukraine. Even under the optimistic RCP2.6 scenario, the frequency and duration of HWs will increase in all regions in the near and mid-term future, with the most significant increase observed in southern and eastern Ukraine. Although the rate of increase in the number of HWs under the RCP2.6 scenario will stabilize by the end of the century, the total number of HWs will remain higher than in the reference period. At the same time, it is expected that by the end of the century, the duration of HWs will even decrease slightly across almost the entire territory of Ukraine compared to the reference period (with the exception of the southern region). A possible explanation for the shorter duration of heat waves at the end of the 21st century under the RCP2.6 scenario is the stabilization of radiative forcing and the corresponding slowdown in the rate of warming. Under these conditions, the further intensification of heat extremes is less pronounced than under scenarios with higher emissions.

Under the RCP8.5 scenario, the projected changes are more significant. The number of HWs is expected to more than double by the middle of the 21st century and to increase more than 2.5 times by 2071–2099 compared to

the reference period. The duration of HWs will also increase, with the average duration expected to increase by approximately 1.5–2 times by the end of the century compared to the reference period, and the maximum duration by 2–3 times. Heat waves may occur throughout the entire summer period. The greatest increase is predicted for the eastern and southern regions of Ukraine. This indicates that these regions may become 'hot regions' with high heat stress levels in the future. Such strong spatial variability in the duration and intensity of HWs highlights the importance of regional adaptation strategies to reduce their impact on people's lives.

The analysis of HW intensity, expressed as both average and maximum HWMId values, depends on the emissions scenario. Under the RCP2.6 scenario, average and maximum intensity tend to decrease or remain close to current values in most regions, except for southern Ukraine, where intensity will increase compared to the current period. Under the RCP8.5 scenario, however, the average and maximum HW intensity increases rapidly across the country. By the end of the century, maximum HWMId values in southern Ukraine are projected to be four times higher than in the reference period.

Overall, these findings indicate that hot periods in Ukraine will not only become more frequent in the future, but also longer and more intense, especially if greenhouse gas emissions remain high. The combination of increased frequency, duration and extreme intensity creates a serious threat to human health, ecosystems, agriculture, energy systems and critical infrastructure.

From a wider perspective, the results of this study highlight the urgent need for mitigation and adaptation measures. The projected changes provide a scientific basis for the development and improvement of climate-resilient urban planning, the Heat Health Warning System and adaptation strategies in Ukraine.

Author's contribution: Olga Shevchenko – conceptualization, formulation of research goals and objectives, methodology, data analysis, formal analysis, writing (original draft, review & editing); Ivan Kostyrko – programming, testing code components, data analysis, visualization, formal analysis, writing (original draft); Iulii Didovets – methodology, databases and data validation, formal analysis, writing (review & editing); Sergii Zapototskyi – conceptualization, formulation of research goals and objectives, writing (review & editing); Valeriia Sazonova – formal analysis, writing (original draft); Sergiy Snizhko – conceptualization, formulation of research goals and objectives, methodology, writing (review & editing).

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ПРОЄКЦІЇ ВИПАДКІВ ХВИЛЬ ТЕПЛА В УКРАЇНІ У XXI СТОЛІТТІ

В с т у п . ***Хвилі тепла (ХТ) добре відомі своїм негативним впливом на здоров'я людини. Вони також можуть призводити до посух, лісових пожеж, скорочення або втрати врожаю, значного навантаження на енергосистеми, руйнування об'єктів інфраструктури та, як наслідок, до суттєвих економічних збитків. Згідно з кліматичними проєкціями, у найближчі десятиліття в багатьох частинах світу очікується подальше підвищення температури повітря та збільшення частоти виникнення ХТ. Пропоноване дослідження спрямоване на оцінку хвиль тепла, що можуть виникати на території України протягом XXI ст., за кількістю, тривалістю й інтенсивністю на основі сценаріїв RCP (Representative Concentration Pathways – укр. репрезентативні шляхи концентрації).***

М е т о д и . ***Було використано підхід із порогом 90-го перцентилю для ідентифікації випадків ХТ, а їхню інтенсивність оцінювали за допомогою щоденного індексу магнітуди хвилі тепла (HWMId). Аналіз було виконано із застосуванням регіональної кліматичної моделі високої роздільної здатності системи EURO-CORDEX (просторова роздільна здатність використаної симуляції становить 0,22°) за сценаріями RCP2.6 та RCP8.5.***

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Р е з у л ь т а т и . ***Результати дослідження свідчать, що частота ХТ в Україні суттєво зростатиме за сценарієм RCP8.5. Очікується, що кількість ХТ більш ніж подвоїться до середини XXI ст. та зросте в понад 2,5 раза в період 2071–2099 рр. порівняно з базовим періодом. Тривалість ХТ також збільшуватиметься: середня тривалість, за прогнозами, зросте приблизно у 1,5–2 рази до кінця століття порівняно з базовим періодом, а максимальна тривалість – у 2–3 рази.***

За сценарієм RCP2.6 частота і тривалість ХТ зростатимуть у близькій і середньостроковій перспективах. Швидкість збільшення кількості ХТ за сценарієм RCP2.6 стабілізується до кінця століття, однак загальна кількість ХТ залишатиметься вищою, ніж у базовому періоді, тоді як тривалість ХТ наприкінці століття навіть дещо зменшиться майже на всій території України порівняно з базовим періодом.

В и с н о в к и . ***Результати дослідження свідчать, що в Україні в майбутньому зросте не лише частота, а також тривалість й інтенсивність випадків хвиль тепла, особливо якщо викиди парникових газів залишатимуться високими. Отримані результати підкреслюють нагальну потребу у впровадженні заходів із пом'якшення наслідків змін клімату й адаптації до спеки в Україні. Прогнозовані зміни створюють наукове підґрунтя для розроблення та вдосконалення кліматостійкого міського планування, системи оповіщення про спекотну погоду, що може зашкодити здоров'ю (Heat Health Warning System), та стратегій адаптації в Україні.***

К л ю ч о в і с л о в а : ***хвиля тепла, проєкції хвиль тепла, індекс магнітуди хвилі тепла, Україна, зміна клімату.***

Декларація про генеративний штучний інтелект та технології, що використовують штучний інтелект. Під час підготовки цієї статті автори не використовували інструменти штучного інтелекту.

Declaration of Generative AI and AI-Assisted Technologies. During the preparation of this work, the authors did not use artificial intelligence tools.

Етична декларація. Дослідження є теоретичним аналізом відкритих джерел і не передбачає безпосередньої взаємодії з людьми чи тваринами. Відповідно, отримання спеціального етичного висновку для такого типу дослідження не потрібно.

Ethical Statement. This study is a theoretical analysis of public sources and does not involve direct interaction with humans or animals. Accordingly, formal ethical approval was not required for this type of research.

Автори заявляють про відсутність конфлікту інтересів. Спонсори не брали участі в розробленні дослідження; у зборі, аналізі чи інтерпретації даних; у написанні рукопису; в рішенні про публікацію результатів.

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