IV. ПРИРОДНИЧО-ГЕОГРАФІЧНІ ДОСЛІДЖЕННЯ

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THE IMPACT OF HEAT WAVES ON THE LEVEL OF AIR POLLUTION IN KYIV

Air pollution level in big cities is heavily influenced by meteorological factors, including heat waves (HWs). During the last decades, the number of HWs and their intensity has increased worldwide including in Ukraine. Heat waves are more intensive in big cities, because of manmade surfaces and fewer green zones. The aim of this study is to investigate the impact of heat waves on the level of air pollution in Kyiv.

The research is based on the concentrations of formaldehyde, nitrogen dioxide, and sulfur dioxide measured on 6 monitoring stations during the summer months of 2017–2021 in Kyiv. These monitoring stations are characterized by very different concentrations of air pollutants. Data from daily observations of maximum air temperature for the periods 1961–1990 and 2017–2021 are employed for the identification of HW episodes for the summer period. To describe pressure conditions favoring the occurrence of heat waves, daily values of sea-level pressure (SLP), the height of the geopotential height of 500 hPa, and temperature on the 850 hPa pressure surface were used.

The research showed the effect of heat waves on the concentrations of nitrogen dioxide, formaldehyde, and sulfur dioxide in the air of Kyiv. The concentrations of these pollutants during the heat wave events at all studied monitoring stations (regardless of the initial level of air pollution) and a gradual decrease in concentrations after the HWs finished have been found. The circulation processes caused to the formation of HWs over the territory of Ukraine were analyzed. It was shown that during the heat waves that occurred in Kyiv within the years 2017–2021, in all cases, except for one, the baric field formed over the studied territory had almost the same structure and shape. It is confirmed that the formations of heat waves in Kyiv are associated with anticyclonic formations in the atmosphere. Therefore, the influence of heat waves on the concentrations of formaldehyde is explained by the fact that during the HWs, there are very favorable conditions for the course of photochemical reactions from precursor substances, which leads to an increase in the concentration of this pollutant, while the influence on the concentrations of sulfur dioxide and nitrogen dioxide is caused by the fact that heat waves are characterized by all features of anticyclonic weather (like low wind speeds (or calm), inversions, etc.) which are favorable conditions for the accumulation of pollutants in the atmosphere.

Keywords: *heat wave, air pollution, formaldehyde, nitrogen dioxide, sulfur dioxide, Kyiv.*

Background

The populations of nearly all big cities worldwide suffer from poor air quality. This has a direct or indirect impact on people's health and lifestyle, as well as their economic activity. According to the Borys Sreznevsky Central Geophysical Observatory, Kyiv ranked eighth among Ukrainian cities subject to state air quality monitoring according to the Air Pollution Index in 2022. The concentrations of nitrogen dioxide and formaldehyde have been exceeding the maximum permissible concentrations for many years in Kyiv, and the concentrations of these pollutants in the warm season are significantly higher than in the cold season *(Shevchenko et al., 2015; Shevchenko et al., 2014; Shevchenko, 2021)*.

Air pollution level in big cities is heavily influenced by meteorological factors, including heat waves. A heat wave (HW) is 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 *(Shevchenko et al., 2022b)*. Since heat waves are associated with anticyclonic weather, characterized by calm or low winds, clear sunny weather, and low air humidity, HWs should create favorable conditions for photochemical reactions in the polluted surface layer of the urban atmosphere and the accumulation of pollutants in the air. Heat waves have the strongest effect on the concentrations of precursors or products of photochemical smog. Theoharatos et al. (2010) found a significant correlation between HWs and mean hourly ozone, nitrogen dioxide, and sulfur dioxide concentrations in Athens. Snizhko and Shevchenko *(Snizhko, Shevchenko, 2015)* showed an increase in formaldehyde and nitrogen dioxide concentration in the air of Kyiv in the example of the summer 2010 mega-heat wave.

HWs can cause simultaneous exposure to extreme heat and high air pollutant concentrations (*Vautard et al. 2007*). In addition, sunny weather encourages outdoor activities, and therefore people suffer more exposure to ozone as well as other pollutants (*Pascal et al., 2021*). This can lead to an increase in the number of cases of morbidity and mortality during heat wave events (*Hoek et al., 2000*). Some authors have attempted to establish the number of additional deaths associated with high levels of air pollution during HW events

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(*Hoek et al., 2000; Stedman, 2004).* This is a very difficult task because it is hard to separate mortality cases related to exposure to prolonged periods of extreme heat and exposure to high concentrations of air pollutants. The concentration for different pollutants, which is taken as a limit when calculating possible fatalities due to their impact on the human body, is usually determined under normal conditions for humans (comfortable air temperature and humidity), without taking into account that in hot weather, much lower concentrations of pollutants in the air can become a lethal dose for the human body. It is necessary to consider the synergistic effect of heat and high concentrations of pollutants on the human body in order to objectively assess the impact of HWs on human health (*Analitis et al., 2018*).

Heat waves are more intensive in big cities, where surfaces are characterized by lower albedo and cause the creation of urban heat islands (*Kalisa et al., 2018*). Mirzaei (*2015*) indicated that higher air temperatures during HWs increase heat- and air-pollution-related mortality in cities.

The number of HWs and their intensity has increased worldwide during the last decades. Extreme HWs were observed all over the world during the last decades. For instance, mega-heat waves were observed in Central Europe in the summer of 1994 (*Tomczyk, Bednorz 2016; Lhotka, Kysely, 2015*), June and August of 2003 (*Fink, et al., 2004; Rebetez, et al., 2006*), in June and July of 2006 (*Rebetez, Dupont & Giroud, 2006; Kysely, 2010; Monteiro et al., 2013*), as well as in Ukraine in the summer of 2010 and in August 2015 (*Shevchenko et al., 2022b*).

Given the increase in air temperature that occurs as a result of climate change and the increase in the frequency and intensity of heat waves, as well as the high concentrations of some pollutants in the air of Kyiv during the warm season, it is obvious that it is highly relevant to study the impact of HWs on air quality. Therefore, this study aims to investigate the impact of heat waves on the level of air pollution in Kyiv.

Data from air pollution monitoring stations (MS) of the Boris Sreznevsky Central Geophysical Observatory were used in this study. The research is based on the concentrations of formaldehyde, nitrogen dioxide, and sulfur dioxide measured on 6 MSs during the summer months of 2017–2021. MS № 5 is situated in the green zone near Nauky Avenue, 37, and characterized by the lowest concentrations in Kyiv. MS №6 situated on Galytska Square, MS № 7 on Besarabska Square, MS №20 on Holosiivska Square, MS № 9 on Kaunaska Street (Left bank of the Dnipro River), MS № 11 Beresteyskyi avenue (near the Svyatoshin metro station). These monitoring stations are situated in places with intensive traffic and therefore characterized by very high concentrations of air pollutants.

Data of daily observations of maximum air temperature for the periods 1961–1990 and 2017–2021, measured at the international standard level of 2 m above ground level, are employed for the identification of HW episodes for the summer months. In this study, a heat wave (HW) is defined as 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 (definition of heat waves recommended by IPCC) (*Frich et al., 2002*). Statistical and graphical processing of the collected data was performed utilizing the Excel program.

To describe pressure conditions favoring the occurrence of heat waves, daily values of sea-level pressure (SLP), the height of the geopotential height of 500 hPa, and temperature on the 850 hPa pressure surface were used. The data were obtained from the archive DWD analysis charts (https://www.wetter3.de/).

An analysis of a series of sea-level pressure maps and maps of constant-pressure surfaces was carried out for the periods when heat waves were observed during 2017–2021. The main baric centers were identified, and the horizontal pressure gradients between these centers and the directions of their movement were analyzed.

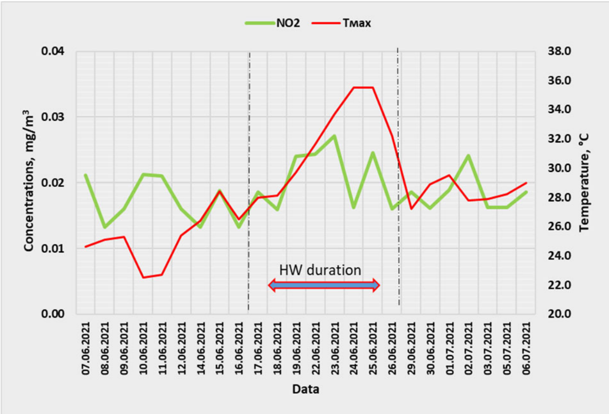
Results

The impact of heat waves on the level of air pollution in Kyiv. The analysis results indicate that during the summer months of 2017–2021, 8 cases of heat waves were observed in Kyiv: 31.07–05.08.2017; 16.08–21.08.2017; 10.06–15.06.2019; 19.06–24.06.2019; 07.06–13.06.2020; 17.06 –26.06.2021; 13.07–19.07.2021; 26.07–02.08.2021. According to the values obtained of the cumulative $T_{a,max}$, the intensity of these HW events was not very high. It ranged between 12.6°C (26.07–02.08.2021) and 26.6°C (16.08–21.08.2017), while the lowest cumulative $T_{a,max}$ during HWs for the long-term period (1961–2015) in Kyiv was 9.8°C and the highest cumulative $T_{a,max}$ was 108.6°C *(Shevchenko et al., 2022a).* The heat waves observed in Kyiv in 2017–2021 were characterized by mean and low duration. The duration of four heat waves was six days, two – seven days, one – eight days, and one – ten, while meat duration HWs in Kyiv in the years 1961–2015 was 9.6 days.

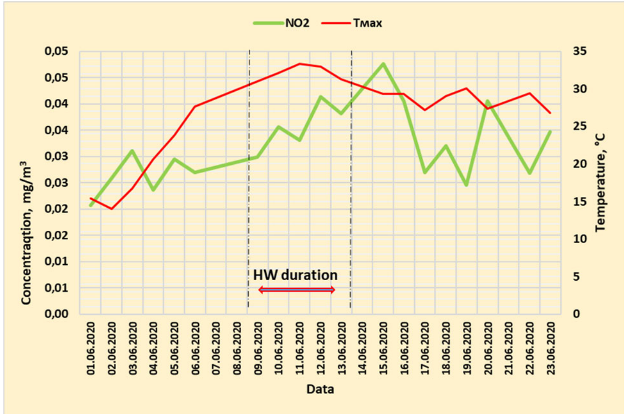
To analyze the influence of heat waves on the air pollution level, the concentrations of formaldehyde, nitrogen dioxide, and sulfur dioxide measured at 13:00 EEST in different parts of Kyiv were analyzed. The periods covering 7 days before the heat wave, the heat wave, and 7 days after it ended were chosen for the study. In total, almost 150 graphs were created and analyzed.

For the study, temperature graphs and air pollutants concentrations were plotted for all MSs for the periods of researched HWs observed in Kyiv in the summer months of 2017–2021. The analysis showed that during HWs, concentrations of nitrogen dioxide in the air of Kyiv increased (fig. 1a, fig. 1b). The concentrations of this pollutant increased at all MSs (regardless of the initial air pollution level) – both at the MS located on Besarabska Square, which is characterized by the highest NO2 concentrations in Kyiv, and at MS № 5, which is characterized by the lowest concentrations. An increase in nitrogen dioxide concentrations was recorded during all the studied HWs. Nitrogen dioxide concentrations gradually decreased after the HWs finished.

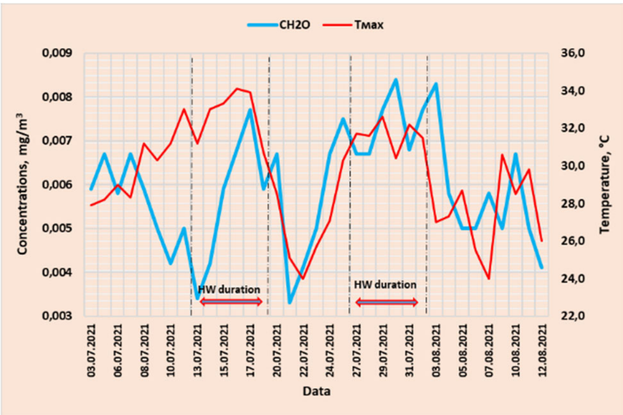
Formaldehyde is a product of photochemical smog and during the warm period, the formation of this pollutant from precursors is an important source of its entry into the atmosphere of big cities with intensive traffic. The analysis of the graphs of the maximum daily air temperature and formaldehyde concentrations during the researched HWs (fig. 1c, fig. 1d) shows that concentrations of this pollutant depend on air temperature. An increase in air temperature causes a rising in the concentrations of formaldehyde in the air of Kyiv. This pattern was found at all monitoring stations, including MS 5, which is characterized by the city's lowest pollution level. After the end of the HWs, concentrations of formaldehyde in the air gradually decreased and, in most cases, reached the level observed before the beginning of this atmospheric phenomenon. The rising sulfur dioxide concentrations during HW cases was found in all researched MSs (fig. 1e, fig. 1f). The increase in air temperature that occurred before the beginning of HW was accompanied by an increase in sulfur dioxide concentrations, and after the end of the HW the concentrations of this pollutant started to decrease.



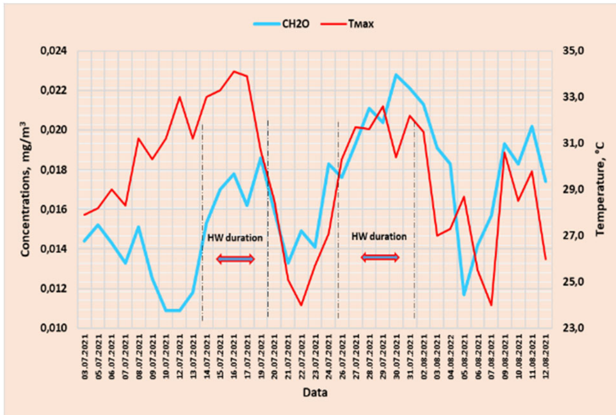
a) nitrogen dioxide concentrations measured on MS № 5



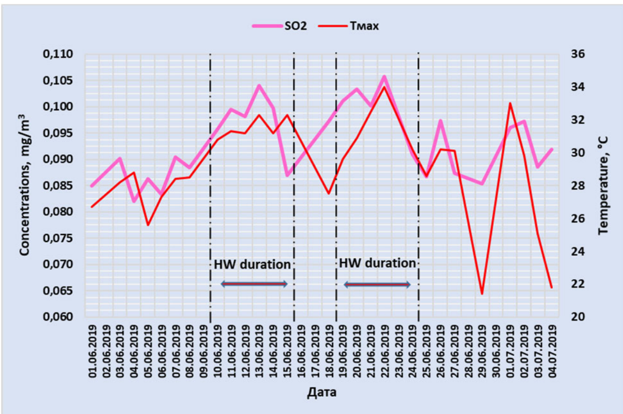
b) nitrogen dioxide concentrations measured on MS № 7



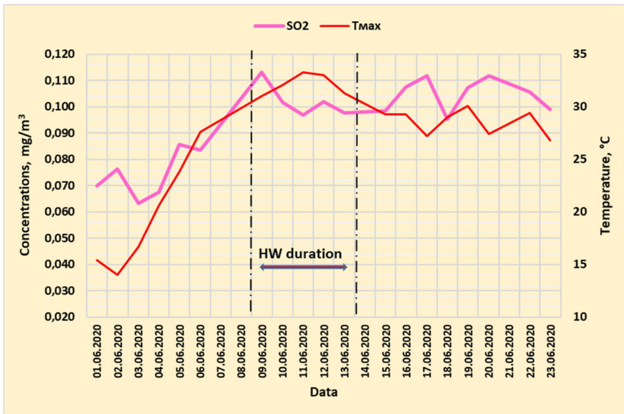
c) formaldehyde concentrations measured on MS № 5



d) formaldehyde concentrations measured on MS № 7



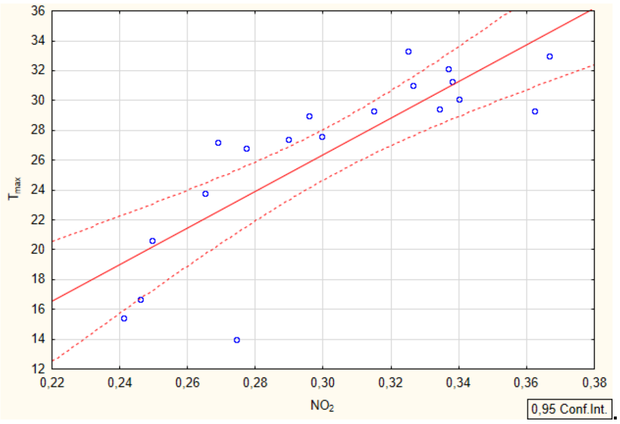
e) sulfur dioxide concentrations measured on MS № 7



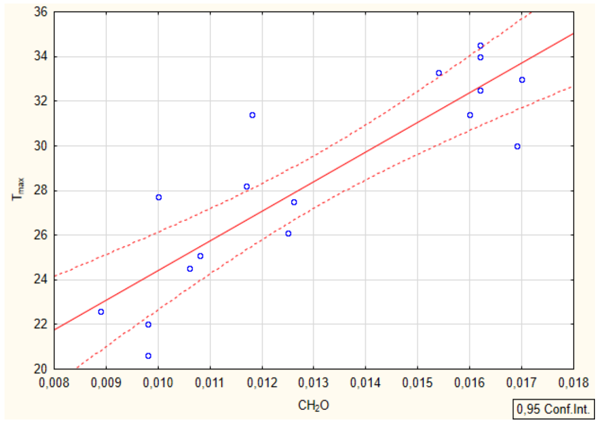
f) sulfur dioxide concentrations measured on MS № 11

Fig. 1. The maximum daily air temperature and concentrations of pollutants at 13 hours EEST during heat wave events

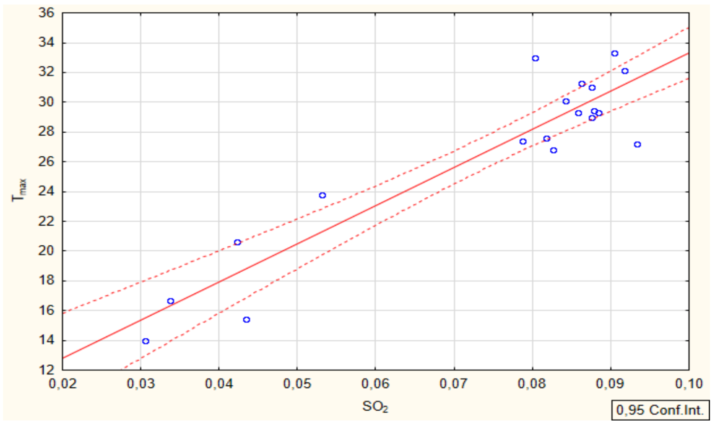
To confirm the influence of air temperature increasing on the concentrations of air pollutants during HWs in Kyiv, a study of correlations for individual cases of heat waves was conducted for some MSs. It was found that the correlation coefficients between temperature and formaldehyde were the highest and, in most cases, amounted to 0.6 and above, while at some MSs they reached 0.8–0.9. The correlation coefficients between air temperature and nitrogen dioxide concentrations and between air temperature and sulfur dioxide concentrations were mostly lower, however, during some HWs the correlation was relatively high (the correlation coefficient also reached 0.8–0.9) (fig. 2). It should be mentioned that high values of the correlation coefficient were found at MSs with different levels of air pollution (both at MS № 5 and MS № 7). A high correlation makes it possible to conclude that air temperature and solar radiation significantly impact the concentrations of formaldehyde in the city air. This confirms the findings of other researchers regarding the impact of solar radiation and air temperature on the formation of formaldehyde in the polluted atmosphere of big cities from precursors. The influence of high air temperature on the increase in formaldehyde concentrations in Kyiv was found by Snizhko and Shevchenko (2015) in the example of the 2010 mega heat wave. The relationship between air temperature and concentrations of sulfur dioxide obviously can be explained by the fact that the heat waves are characterized not only by high air temperature and sunny weather (which are favorable conditions for photochemical reactions) but also all features of anticyclonic weather (like low wind speeds (or calm), inversions, etc.) which is observed during the heat wave events. The influence of anticyclonic weather on the increasing air pollution level was found in the 70s of the XX century but the synoptic conditions generating heat waves on the territory of Ukraine are still underestimated as well as the mechanism of influence of HWs on the rising of air pollution level in big cities.



a) dependence between nitrogen dioxide and air temperature on MS № 7 during the HW 9–13.06.2020



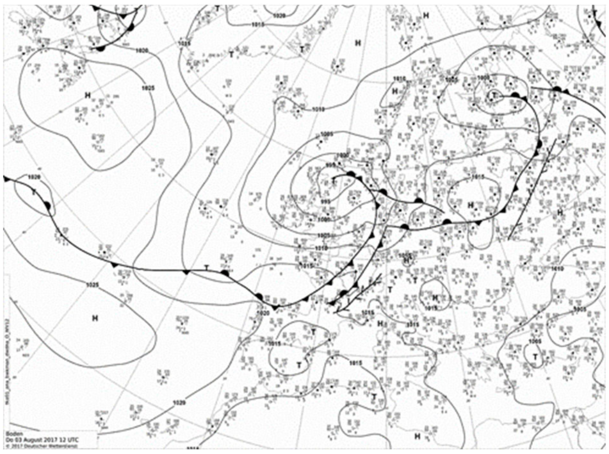
b) dependence between formaldehyde and air temperature on MS № 20 during the HW 16–21.08.2021



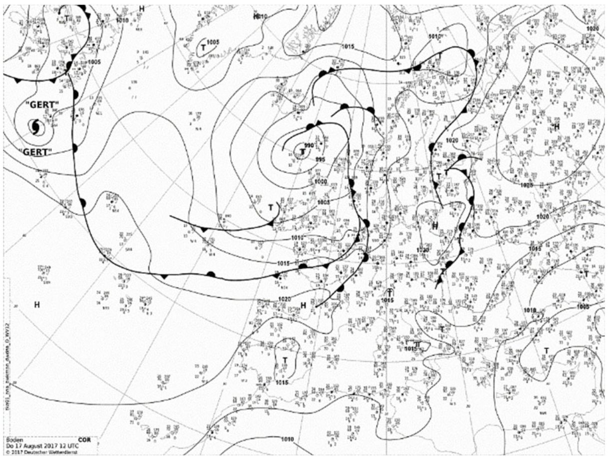
c) dependence between sulfur dioxide and air temperature on MS № 9 during the HW 09–13.06.2020

Fig. 2. Dependence between air pollutants concentrations and air temperature during the heat wave events in Kyiv

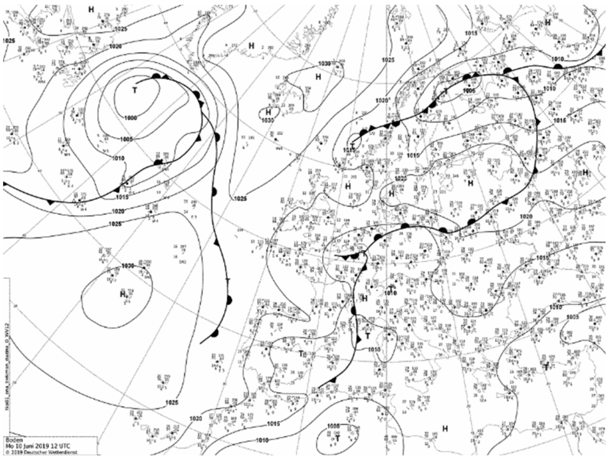
Atmospheric circulation during heat waves in the period 2017–2021. As mentioned above during the summer months of 2017–2021, 8 heat waves were observed in Kyiv. In all cases, except for one, the baric field formed over the studied territory had almost the same structure and shape. Atmospheric circulation was determined by almost identical baric systems and directions of movement of these systems. Sea-level pressure ranged from 995 to 1030 hPa with minimum values in cyclones over Iceland, Nova Zemlya, and Great Britain and maximum values in the centers of anticyclones formed over the continent and the Azores. In general, there is a drop in pressure from the Mediterranean and Black Sea coasts of Europe to the north of Scandinavia (fig. 3).



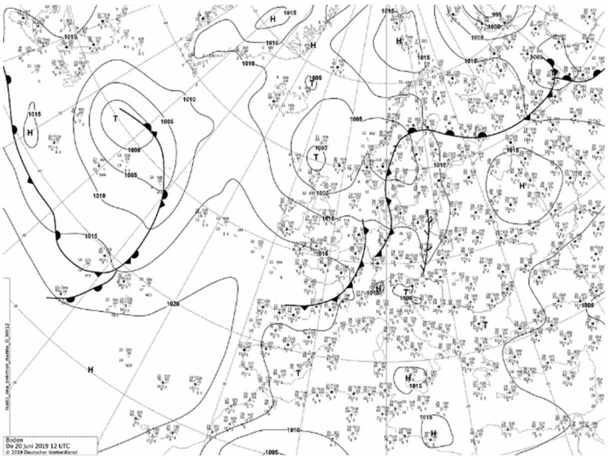
a) 03 August 2017 12:00 UTC



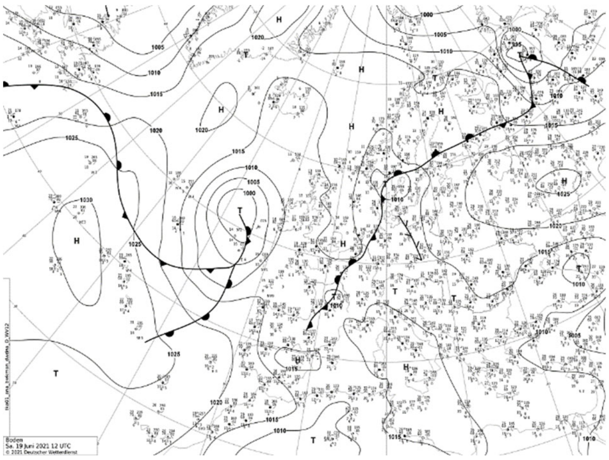
b) 17 August 2017 12:00 UTC



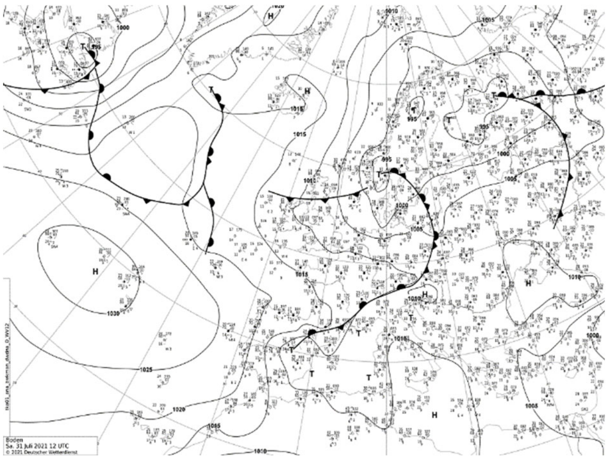
c) 10 June 2019 12:00 UTC



d) 20 June 2019 12:00 UTC



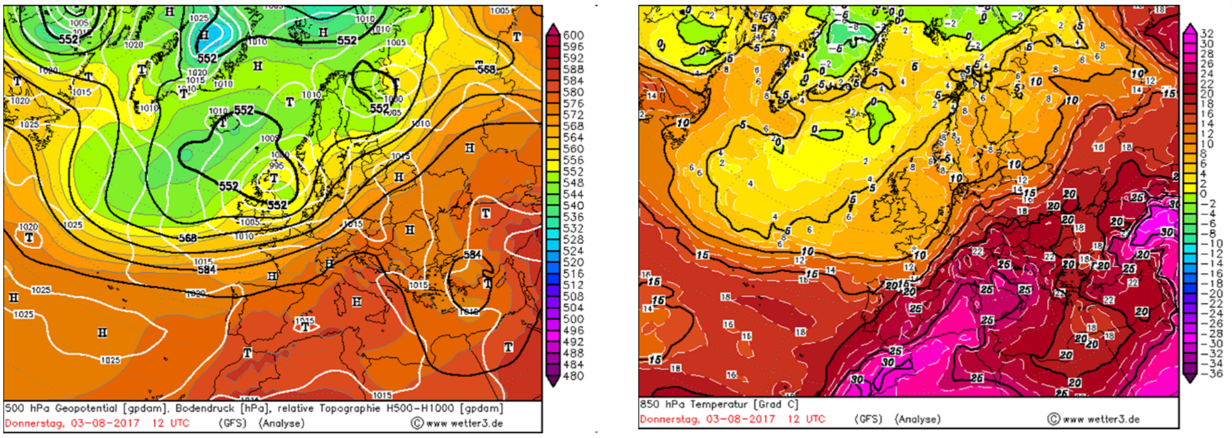
e) 19 June 2021 12:00 UTC



f) 31 July 2021 12:00 UTC

Fig. 3. Sea level pressure (hPa) during heat waves in Kyiv

Larger horizontal pressure gradients are observed over pressure centers over the ocean, and less significant gradients over the continent. On the 500 hPa constant-pressure surface, it was found that during heat waves, this surface has bigger heights along the line from the Iberian Peninsula, along the coast of the Mediterranean Sea, Ukraine, and the western territories of russia bordering Ukraine. Gradually, the 500 hPa constant-pressure surface slopes northwest toward the North Atlantic. The air temperature on the 850 hPa constant-pressure surface decreased from > 25°C over the Mediterranean Sea to the northwest < 0°C. One such example is the case of the heat wave in Kyiv on August 3, 2017 (fig. 4).



a) height of 500 hPa constant-pressure surface (gpm) **b) temperature on the 850 hPa constant-pressure surface (°C)**

Fig. 4. The maps of the height of 500 hPa constant-pressure surface and temperature on the 850 hPa constant-pressure surface on August 3, 2017

This distribution of atmospheric pressure causes circulation, which determines the conditions that lead to heat waves over Southern, Central, and Eastern Europe.

The occurrence of heat waves in Eastern Europe during the studied period was associated with a ridge of high pressure passing through Europe from the Iberian Peninsula to the northern regions of russia. Closed areas of high pressure (up to 1020–1030 hPa) are formed within this ridge, which determine the weather conditions over the territory where they are stationed. The surface slope of 500 hPa with maximum heights over the eastern part of the continent and a slope to the northwest further confirms the presence of warm air masses over the study area, since temperature and air density are closely related: warm air masses are less dense than cold masses, and therefore the pressure drop with height in warm air masses occurs more slowly.

The circulation system described above provided a powerful influx of solar radiation, due to little or zero cloud cover. Such conditions are characteristic of anticyclonic weather. In almost all investigated cases of heat waves, except for one, the sea-level pressure, which determined the weather conditions over the studied territory, had the same structure and shape. And in the case that was different, in general, the main regularities of the distribution of the pressure field within the studied territory were the same as in the other cases of heat waves.

Thus, during the studied period of 2017–2021, during the heat waves that occurred in Kyiv, the sea-level pressure field was determined by the same circulation processes and the distribution of the main baric centers over the Atlantic, Europe, and the neighboring territories of russia. The baric centers that determined the conditions for the formation of heat waves in Kyiv were distributed as follows: a baric ridge stretched along the coast of the Mediterranean Sea from the Azores, the Iberian Peninsula, through Italy, the Balkans, Ukraine, belarus, and the northwestern regions of russia. Within this area of high atmospheric pressure, closed centers with a pressure of 1020–1030 hPa were formed. Most often, these closed areas are formed over the Azores Islands and the territory of belarus. In turn, the large ridge of high pressure is blocked by deep closed areas of low pressure (995–1000 hPa), which are formed over Great Britain, the Scandinavian Peninsula, and northwestern regions of russia and Turkey. Such circulation conditions in summer lead to the emergence of such a phenomenon as heat waves over Southern, Central, and Eastern Europe. After all, stable anticyclonic weather with low or zero cloud cover is formed over these regions. This contributes to additional overheating of the air, which is stationary over one area for a long period. The situation may be further aggravated by the advection of hot air from the territory of North Africa.

Discussion and conclusions

The atmospheric circulation conditions during heat wave events in Kyiv for the period 2017–2021 were similar to the atmospheric conditions during HW events observed in Eastern Europe during 1973–2010 *(Tomczyk, 2017),* and in lowland Germany over the period 1966–2015 *(Tomczyk, Sulikowska, 2018).* Anticyclonic conditions over Western Europe, due to the subsidence of air masses, provided cloudless weather, which intensified solar radiation flux as shown in the research study of Tomczyk, Potrolniczak & Bednorz (2017). There are also several studies of the circulation conditions that lead to the appearance of heat waves in some regions of Europe. These papers show that this occurs in most cases under anticyclonic weather conditions that have the effect of enhancing insolation *(Fink et al. 2004; Rebetez et al., 2006; Founda, Giannakopoulos, 2009).*

A synoptic pattern was identified in which the northern regions of Africa were under the combined influence of an anticyclonic area to the north and a trough over the Sahara extending the depression centered in the south. This was shown for two cities in Morocco: Casablanca and Marrakech, between 2010 and 2019. *(Khomsi et al., 2022).*

The occurrence of heat waves in Kyiv was related to a ridge of high-pressure lying over Europe, within which there was a local high-pressure area formed with its center over the belarus and the northwestern regions of russia. A similar circulation type causing the occurrence of heat waves in Central Europe is a low-pressure area with its center to the west of Ireland *(Tomczyk, Bednorz, 2016).*

The effect of heat waves on the concentrations of nitrogen dioxide, formaldehyde, and sulfur dioxide in the air of Kyiv was shown. An increase in the concentrations of these pollutants during the heat wave events at all studied monitoring stations (regardless of the initial level of air pollution) and a gradual decrease in concentrations after the heat wave is completed is determined. The influence of air temperature on the concentrations of formaldehyde is explained by the fact that during the heat waves, there are very favorable conditions for the course of photochemical reactions from precursor substances, which leads to an increase in the concentration of this pollutant. The relationship between air temperature and concentrations of sulfur dioxide and nitrogen dioxide is caused by the fact that heat waves are characterized not only by high air temperature and sunny weather (which are favorable conditions for photochemical reactions) but also by all features of anticyclonic weather (like low wind speeds (or calm), inversions, etc.) which are favorable conditions for the accumulation of pollutants in the atmosphere.

In order to confirm the influence of stable anticyclonic weather during heat waves on the air pollution level, the circulation processes cause to the formation of HWs over the territory of Ukraine were analyzed. It was shown that the same circulation conditions for the formation of heat waves were found in all researched cases, except for one. Namely, an area of high atmospheric pressure stretched along the coast of the Mediterranean Sea from the Azores, the Iberian Peninsula, through Italy, the Balkans, Ukraine, belarus, and the northwestern regions of russia. Closed centers with a pressure of 1020–1030 hPa were formed within this area. Most often, they are formed over the Azores Islands and the territory of belarus. The large ridge of high pressure is blocked by deep closed areas of low pressure (995–1000 hPa), which are formed over Great Britain, the Scandinavian Peninsula, and the northwestern regions of russia and Turkey. Such circulation conditions lead to the emergence of heat waves in summer not only over Kyiv, but also over Southern, Central, and Eastern Europe. Thus, it was confirmed that the formations of heat waves in Kyiv are connected with anticyclonic formations in the atmosphere which will contribute to the accumulation of pollutants in the atmospheric air and, therefore, during periods of HWs, the population of Kyiv experiences both a strong health negative impact of heat and high concentrations of air pollutants.

Authors contribution information: Olga Shevchenko – conceptualization, methodology, the writing is an original draft, writing – revising and editing; Yuliia Yatsenko – formal analysis, methodology, the writing is an original draft; Diana Kryvobok – formal analysis, data validation; Sergiy Snizhko – conceptualization, writing – revising and editing.

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ВПЛИВ ХВИЛЬ ТЕПЛА НА РІВЕНЬ ЗАБРУДНЕННЯ АТМОСФЕРНОГО ПОВІТРЯ МІСТА КИЄВА

На рівень забруднення атмосферного повітря великих міст значною мірою впливають метеорологічні чинники, зокрема хвилі тепла (ХТ). Протягом останніх десятиліть кількість й інтенсивність хвиль тепла зросла в усьому світі, включаючи Україну. Хвилі тепла є інтенсивнішими у великих містах у зв'язку з наявністю штучних поверхонь і меншою кількістю зелених зон. Метою дослідження є вивчення впливу хвиль тепла на рівень забруднення атмосферного повітря в місті Києві.

Для виконання цієї розвідки використано інформацію про концентрації формальдегіду, діоксиду азоту й діоксиду сірки, виміряні на шести постах спостереження за забрудненням повітря (ПСЗ), протягом літніх місяців у 2017–2021 рр. у Києві. Для ідентифікації випадків ХТ у літні місяці застосовано максимальну добову температуру повітря за 1961–1990 і 2017–2021 рр. Для опису синоптичних умов, які сприяють формуванню хвиль тепла, використано добові значення тиску на рівні моря (висота геопотенціалу 500 гПа, температура на поверхні 850 гПа).

Установлено вплив хвиль тепла на концентрації діоксиду азоту, формальдегіду й діоксиду сірки в атмосферному повітрі міста Києва. Показано зростання концентрацій цих забруднювальних речовин (ЗР) під час ХТ на всіх досліджуваних ПСЗ (незалежно від вихідного рівня забруднення повітря) та поступове зниження їхніх концентрацій після завершення ХТ. Проаналізовано циркуляційні процеси, що призводять до утворення ХТ над територією України. Показано, що під час хвиль тепла, які спостерігалися в Києві протягом 2017–2021 рр., у всіх випадках, за винятком одного, баричне поле, яке формувалося над досліджуваною територією, мало майже однакову структуру й форму. Підтверджено, що формування ХТ у Києві пов'язане з антициклонічними утвореннями в атмосфері. Показано, що вплив хвиль тепла на концентрації формальдегіду пояснюється тим, що під час ХТ виникають дуже сприятливі умови для перебігу фотохімічних реакцій з речовин-прекурсорів, що призводить до збільшення концентрацій цієї ЗР, тоді як вплив на концентрації діоксиду сірки й діоксиду азоту зумовлений тим, що для ХТ характерні всі ознаки антициклонічної погоди (низькі швидкості вітру (або штиль), інверсії тощо), які є сприятливими умовами для накопичення ЗР в атмосфері.

К л ю ч о в і с л о в а ***: хвиля тепла, забруднення повітря, формальдегід, двоокис азоту, двоокис сірки, Київ.***

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