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Changes in air temperature frequency in Europe as a component of climate change

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Abstract

The main features of air temperature change in Europe, particularly in Ukraine, are described. In general, the rate of air temperature increase in the studied area exceeds the global average. The warming observed in Western Europe and in mountainous regions is less pronounced than in Eastern Europe. In particular, the mean annual air temperature in Ukraine has risen by more than 3 °C since the beginning of meteorological observations in the late nineteenth century. This warming corresponds to an approximate southward shift of the country's climatic zone by about 500 km. A common feature of recent climate change is the acceleration of air temperature increase. A comparison of data for two equal periods (1961–1990 and 1995–2024) shows a significant increase in the frequency of high-temperature events. Consequently, the probability of hot days during 1995–2024 was substantially higher than during 1961–1990. A characteristic feature of mean daily temperatures across most of Europe, especially in its eastern part, is bimodality in the frequency distribution. In many cases, a peak with a high frequency of occurrence is observed at about 0–2 °C, which is close to the temperature of snow melting. Another common feature, mainly observed in Eastern Europe, is the presence of a right-hand peak at much higher temperatures. At the same time, in Western Europe and in mountainous regions, bimodality is much less pronounced.

Key words:
air temperature, recurrence, phase transitions, bimodality

1 INTRODUCTION

Global warming is one of the most pressing global challenges, affecting the entire planet, including its flora and fauna, the economy, and most importantly, human health.

A large number of scientific studies have been devoted to the rise in air temperature (Boychenko et al., 2016; Ciornei et al., 2022; Dumitrescu et al., 2014; Georgieva et al., 2022; IPCC, 2022; Karamushka et al., 2022; Ionita et al., 2025a, 2025b; Shevchenko et al., 2020, 2022; Tomczyk & Bednorz, 2023; Twardosz et al., 2021; Vyshnevskyi, 2025; Vyshnevskyi & Donich, 2021). According to the World Meteorological Organization (WMO), 2024 was the warmest year on record. The mean global air temperature in 2024 reached 15.1 °C. The global average surface temperature was 1.55 °C (±0.13 °C) above the 1850–1900 average. Prior to 2024, the warmest year had been 2023, with a global average temperature of 15.0 °C.

At the same time, the rate of air temperature increase varies across regions. According to WMO statements and the IPCC report (2022), the rise in air temperature in Europe exceeds the global average. A similar conclusion has been reported in numerous studies (Boychenko et al., 2016; Ciornei et al., 2022; Dumitrescu et al., 2014; Georgieva et al., 2022; Karamushka et al., 2022; Ionita et al., 2025b; Shevchenko et al., 2020, 2022; Tomczyk & Bednorz, 2023; Vyshnevskyi, 2025). According to the study (Ionita et al., 2025b), the mean summer temperature across Europe in 2024 was the highest on record, with a temperature anomaly of +1.54 °C relative to the 1991–2020 climatological mean, exceeding the previous high of +1.34 °C recorded in 2022.

A common feature of contemporary climate change is the acceleration of air temperature increase. This trend is observed in both lowland and mountain regions. In particular, such results are presented in the paper by Ionita et al. (2025a), in which data from two stations – Hohenpeißenberg (elevation 977 m a.s.l.) and Zugspitze (elevation 2956 m a.s.l.) – were analysed. The mean increase in air temperature at the Hohenpeißenberg station during 1901–2024 was 0.20 °C per decade, whereas in 1981–2024 it reached 0.51 °C per decade. In turn, the mean annual increase in air temperature at the Zugspitze station was 0.13 °C per decade in 1901–2024, while in 1981–2024 it was approximately three times higher, reaching 0.41 °C per decade.

A similar results can be found in the article (Twardosz et al., 2021), in which was carried out a spatial analysis of air temperature based on data from 210 meteorological stations across Europe. According to that study, during 1951–2020 the increase in air temperature over most of Europe ranged from 0.25 to 0.35 °C per decade. A markedly higher warming rate was observed in recent decades, particularly in 1985–2020. During this latter period, the greatest increase in air temperature (0.65–0.70 °C per decade), excluding the Arctic region, was recorded in eastern Belarus, in the north-eastern part of Ukraine and adjacent territories of Russia.

The acceleration of air temperature increase over the territory of Ukraine was reported also in the article (Vyshnevskyi, 2025). The mean air temperature during the most recent period (2011–2024) was significantly higher than in 2001–2010 and substantially higher than in 1991–2000 and earlier periods.

Along with the rise in annual and mean monthly temperatures, an increase in low-probability air temperature values has been observed; in other words, the likelihood of extremely high temperatures is growing. This trend indicates a higher probability of extreme heat events, which may have adverse impacts on human health, vegetation, and other sectors.

Episodes of high air temperature have also been described in numerous scientific studies (Boboc et al., 2025; Galanaki et al., 2023; Shevchenko et al., 2020, 2022; Zschenderlein et al., 2019). Such events are usually classified as heat waves. According to many studies, the frequency of heat waves is increasing.

An interesting feature observed in many regions of Europe is the bimodality of air temperature, that is, the presence of two temperature intervals with high repeatability. This feature is described, in particular, in the study by Pekar et al. (2024). In that paper, air temperature repeatability was analysed at six meteorological stations in Slovakia located at different altitudes, ranging from lowland sites to mountain stations up to 2635 m a.s.l. In all cases, a pronounced peak in repeatability occurs at temperatures of about 0–2 °C. The authors explain this feature by the high latent heat associated with the phase transition between ice and water. When water freezes, latent heat is released. During the winter season, snow- and ice-covered surfaces and the adjacent air layer are thermally coupled.

In addition to this peak in the 0–2 °C range, a second peak at substantially higher temperatures is observed, mainly at lowland meteorological stations. The position of this second peak depends on altitude: at a station located at 115 m a.s.l., it corresponds to temperatures of 16–18 °C; at 642 m a.s.l., to 12–14 °C; and at 972 m a.s.l., to 10–12 °C. At higher altitudes, the peak associated with relatively warm temperatures practically disappears (Pekar et al., 2024).

Another feature of the air temperature distribution is its asymmetry. In many cases, negative skewness is observed, i.e., the mean value is lower than the mode. In other words, occurrences of relatively high temperatures are more frequent than occurrences of very low temperature (Pekar et al., 2024).

Similar results, namely the bimodality of air temperature, have been reported in several other studies (Grace & Curran, 1993; Matiu et al., 2015). In the study by Matiu et al. (2015), carried out for Western Europe, the bimodality of air temperature was interpreted as a mixture of four seasonal distributions. The air temperature distribution in Australia also exhibits an asymmetric pattern, but with positive skewness (Grace & Curran, 1993).

In our opinion, the repeatability of mean daily and maximum daily air temperatures has not been sufficiently investigated. Therefore, the main objective of our research is to identify this repeatability, with particular emphasis on the phenomenon of bimodality in the air temperature distribution.

2 STUDY AREA AND METHODS

Study area

The focus of this study is Europe, mainly its central part, excluding the most remote regions. Data from eight meteorological stations located in areas with different climatic conditions were used for the analysis.

One station, Helsinki, is located in the north of Europe near the seashore. Another station, Bonn, can be considered representative of central Western Europe. In addition, data from four meteorological stations evenly distributed across the lowland part of Ukraine – from the north (north-east) to the south – were included. One of these stations, Odesa, is located only 200 m from the seashore.

In addition to these six lowland stations, climatic conditions in mountainous areas were also examined. One such station, Mont Aigoual, is located in southern France at an altitude of 1567 m a.s.l. An even higher elevation characterizes the Zugspitze meteorological station (2956 m a.s.l.), located in southern Germany in the Alps (Fig. 1).

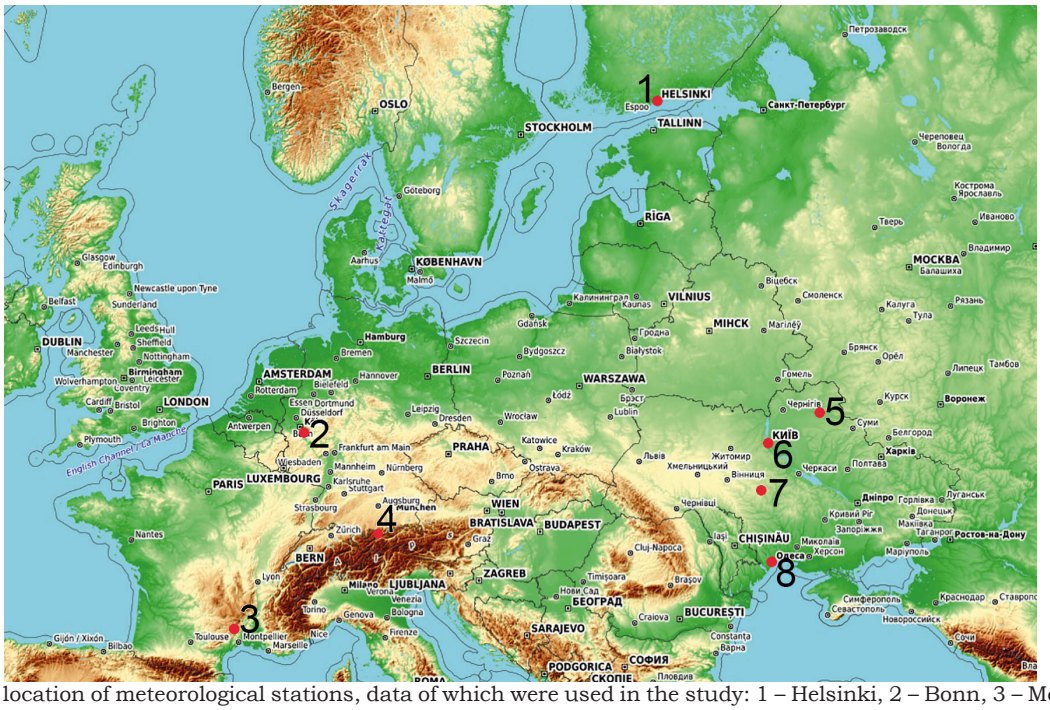


Fig. 1. The location of meteorological stations, data of which were used in the study: 1 – Helsinki, 2 – Bonn, 3 – Mont-Aigoual, 4 – Zugspitze, 5 – Konotop, 6 – Kyiv, 7 – Uman, 8 – Odesa
(source: https://opentopomap.org, edited by the author)

One of the reasons for selecting the above-mentioned stations is the significant observation period and the absence of gaps in the measured data. It should also be noted that Zugspitze is one of the highest meteorological station in Europe. Moreover, these stations and the corresponding results based on their data are well known in the scientific literature (Ionita et al., 2025a).

Most of the meteorological stations whose data were used in this study are not located in large cities. The only exception is Kyiv; however, this station is located far from the city center, in a park area.

The long-term mean annual air temperature (1991–2020) differs considerably among the meteorological stations. For example, its value at Helsinki is 6.5 °C. A much higher mean annual air temperature (10.7 °C) is characteristic of Bonn station, which is located further west and south. The mean air temperature at the Ukrainian stations located to the east and south was as follows: Konotop – 8.0 °C, Kyiv – 9.0 °C, Uman – 8.8 °C, and Odesa – 11.3 °C. In general, temperatures in the range of 8–11 °C are typical for most of the territory of Ukraine.

Lower air temperature is observed in mountainous areas. At Mont Aigoual station, the mean air temperature is 5.7 °C, which is even lower than in Helsinki. The lowest mean annual air temperature (minus 3.8 °C) is recorded at the alpine meteorological station Zugspitze.

During 1991–2020, the mean July air temperature (usually the warmest month) at the studied meteorological stations was as follows: Helsinki – 17.7 °C, Bonn – 19.0 °C, Mont-Aigoual – 13.8 °C, Zugspitze – 3.4 °C, Konotop – 20.7 °C, Kyiv – 21.3 °C, Uman – 20.9 °C, and Odesa – 23.4 °C.

The mean January air temperature (usually the coldest month) at the studied meteorological stations was as follows: Helsinki – minus 3.2 °C, Bonn – +3.0 °C, Mont-Aigoual – minus 1.0 °C, Zugspitze – minus 10.1°C, Konotop – minus 4.5 °C, Kyiv – minus 3.2 °C, Uman – minus 3.4 °C, and Odesa – minus 0.4 °C.

The mean annual precipitation during 1991–2020 was 645 mm at Helsinki, 569 mm at Konotop, 618 mm at Kyiv, 586 mm at Uman, and 466 mm at Odesa. The highest mean annual precipitation was recorded at the Mont Aigoual station, reaching 1970 mm.

Materials and methods

The main source of data for this study was the website https://www.ecad.eu/dailydata/predefinedseries.php, which stores observational data from numerous meteorological stations across Europe. The website includes a file entitled stations.txt, which makes it possible to identify the identification numbers and names of the selected stations. The required datasets were subsequently downloaded and processed.

Some information on climatic conditions at Helsinki station was taken from the website of the Finnish Meteorological Institute (https://en.ilmatieteenlaitos.fi/statistics).

Mean daily and maximum daily air temperatures were ranked using Microsoft Excel. The subsequent analysis was based on histogram construction, with recurrence calculated in 1 °C intervals.

Some additional meteorological data were obtained from the Ventusky platform (https://www.ventusky.com).

In addition, long-term air temperature data from meteorological station Pozhezhevska, which is the highest in Ukraine (1451 m a.s.l.), archived at the Central Geophysical Observatory, were used.

3 RESULTS

The air temperature increase

The available observation data from the eight above-mentioned stations show a clear trend of increasing air temperature. It is important to note that this increase exceeds the global average. In particular, the rise in air temperature over the territory of Ukraine during the observation period, which began at the end of the 19th century, amounts to about 3 °C or even more (Fig. 2).

The available data shows that the increase in air temperature in Ukraine is approximately twice as high as the global average. As in the rest of the world, 2024 was the warmest year on record in Ukraine over the entire observation period.

As can be seen in Figure 2, a polynomial trend line (dark red) provides a better fit to the observed changes in air temperature than a linear one. Similar features of climate change have been reported in other studies (IPCC, 2022; Karamuska et al., 2022; Vyshnevskyi, 2025; Vyshnevskyi & Donich, 2021).

The observed rise in air temperature corresponds to a southward shift of the country's climate zone by approximately 500 km (Vyshnevskyi, 2025).

The increase in air temperature at the other meteorological stations whose data were used in this study is somewhat smaller. For example, at Zugspitze station, the increase over the period 1901–2024 was 0.13 °C per decade, or 1.6 °C in total. Similar to the global and Ukrainian trends, the highest mean annual air temperature at this station (minus 2.2 °C) was observed in 2024.

The increase in air temperature significantly affected the mean values for the period 1995–2024 compared to 1961–1990. However, this difference varies among stations. In particular, at Helsinki station, the mean air temperature was 5.0 °C in 1961–1990 and 6.5 °C in 1995–2024. The difference at Bonn station is smaller: the mean temperature was 9.8 °C in 1961–1990 and 10.9 °C in 1995–2024.

A somewhat larger increase is observed in Ukraine. During the last three decades (1995–2024), the mean air temperature was as follows: Konotop – 8.5 °C, Kyiv – 9.2 °C, Uman – 9.2 °C, and Odesa – 11.6 °C. In 1961–1990, these values were significantly lower: Konotop – 6.7 °C, Kyiv – 7.7 °C, Uman – 7.4 °C, and Odesa – 10.1 °C. Thus, the increase ranges from 1.4 to 1.8 °C.

A smaller rise is observed in mountainous areas. At Mont-Aigoual station, the mean air temperature was 4.5 °C in 1961–1990 and 5.8 °C in 1995–2024. The smallest increase is recorded at Zugspitze station, which has the highest elevation. There, the mean air temperature changed from minus 4.7 °C in 1961–1990 to minus 3.7 °C in 1995–2024.

The available data indicate that the increase in air temperature in mountainous regions is smaller than in lowland areas. This feature is confirmed by observational data from Pozhezhevska mountain station, the highest station (1451 m a.s.l.) in the Ukrainian sector of the Carpathian Mountains. The mean air temperature at this station was 2.7 °C in 1961–1990 and 3.7 °C in 1995–2024.

These results are similar to those obtained in the study by Ionita et al. (2025a). It is worth noting that the mean air temperature during the most recent period (2011–2024) was significantly higher than in 2001–2010 and markedly higher than in 1991–2000. An analysis of Figure 2 shows that with each successive decade, the increase in air temperature becomes more pronounced.

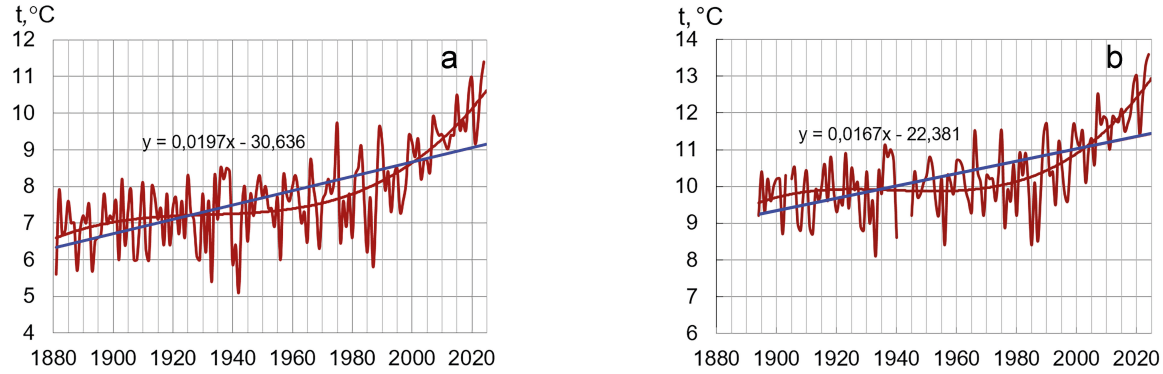


Fig. 2. Long-term changes in mean annual air temperature at Kyiv (a) and Odesa (b) meteorological stations during the observation period. The polynomial trend is shown by a dark red line, and the linear trend is shown by a blue line

For example, the mean annual air temperature in Kyiv reached 11.4 °C in 2024, exceeding the previous record set in 2020 by 0.5 °C.

An increase in air temperature is observed throughout the year. In Ukraine, the most significant rise occurs during January–April and the summer months, while the smallest changes are recorded in May, September, and October (Vyshnevskyi, 2025).

Bimodality of air temperature

A characteristic feature of air temperature recurrence observed at many meteorological stations, particularly those located in lowland areas with cold winters, is bimodality, as reported in previous studies (Grace and Curran, 1993; Matiu et al., 2015; Pekar et al., 2024). The left-hand peak of the distribution corresponds to temperatures of 0–2 °C, which is slightly above the melting point of ice or the freezing point of water (Fig. 3).

The presented figure shows the existence of two distinct peaks in air temperature at Helsinki station. The left peak corresponds to 0–2 °C, while the right one corresponds to 15–17 °C. Two peaks are also observed at Bonn station, but they are less pronounced.

It can be seen that in both cases the curves have shifted to the right, indicating an increase in air temperature over the last decades. At the same time, the left peak at the Helsinki station has remained in the same position.

The existence of two peaks is also characteristic of meteorological stations located in Ukraine (Fig. 4).

As can be seen in Figure 4, a pronounced recurrence peak corresponding to air temperatures of 0–2 °C is characteristic of most of the territory of Ukraine. This feature is much less distinct only in the southern regions and along the seacoast (Odesa station).

In general, the shift of the curves toward higher air temperatures over the territory of Ukraine is greater than at Helsinki and Bonn stations. This indicates a more significant increase in air temperature compared to Helsinki and Bonn.

It should be noted that in most cases, with the exception of Odesa, the position of the left peak has not changed.

Some specific features characterize the recurrence of daily air temperature under mountain conditions at Mont-Aigoual and Zugspitze meteorological stations. In both cases, a significant recurrence of mean daily air temperature near 0 °C is observed. At Mont-Aigoual station, in addition to the peak near 0 °C, a weakly pronounced peak at higher temperatures is also observed. At Zugspitze station, the mode with temperatures higher than 0 °C is absent (Fig. 5).

This feature is similar to the results of a study devoted to air temperature in the Carpathian Mountains and described in the article (Pekar et al., 2024).

Under mountain conditions, a shift of air temperature toward higher values is observed, while the modes remain in their previous positions. Overall, the increase in mean air temperature in mountainous regions is smaller than in the lowland territory.

Changes in the recurrence of high air temperatures

In addition to the increase in annual and monthly mean temperatures, a shift of mean daily temperatures toward higher values is also observed. This shift can be analyzed based on the probability distribution of air temperature. Even in Western Europe, which has a mild climate, a significant increase in rare-probability mean daily temperatures is observed.

In particular, this can be seen in the observational data from the Bonn station. Calculations of rare-probability air temperatures show a significant increase over the past 30 years, both for mean daily and maximum daily air temperatures (Fig. 6).

The data shown in Figure 6 indicate that the

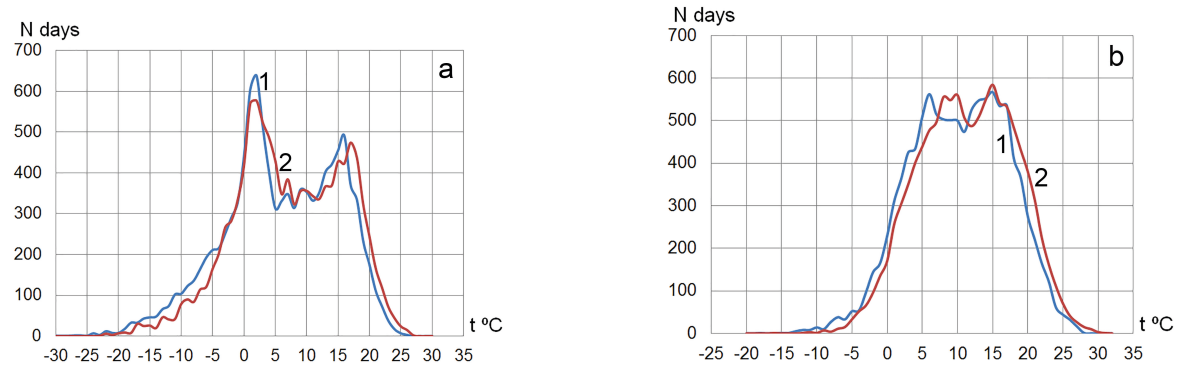


Fig. 3. Histograms of mean daily air temperature at meteorological stations Helsinki (a) and Bonn (b) during 1961–1990 (1) and 1995–2024 (2)

mean daily temperature in Bonn during the period 1961–1990 with a 0.1% probability (approximately once every three years) was 26.7 °C. Over the last 30 years, the air temperature with the same probability has become significantly higher – to 28.2 °C.

Simultaneously, the number of hot days in Bonn greatly increased. During 1961–1990, there were 14 days with mean daily temperatures in the range of 26.0–26.9 °C and 6 days in the range of 27.0–27.9 °C. Higher values were not observed. During the last 30 years (1995–2024), the number of such days increased several times: 28 days with temperature in the range of 26.0–26.9 °C, 16 days in the range of 27.0–27.9 °C, 10 days in the range of 28.0–28.9 °C, and 3 days with even higher temperatures.

A similar increase is observed for maximum daily air temperature. In this case, the probability of hot days in Bonn has increased several times. For example, the probability of a maximum daily temperature of 36 °C during 1961–1990 was about 0.015%, whereas during 1995–2024 it increased to about 0.2%, i.e., more than ten times higher.

The maximum daily air temperature with a 0.1% probability at the Bonn station was approximately 34.7 °C in the first period and 37.2 °C in the second period.

Similar changes are also observed over the territory of Ukraine. The data presented in Figure 7 indicate that the mean daily temperature in Kyiv during the first period with a 0.1% probability (approximately once every three years) was 26.4–26.5 °C. Over the past 30 years, the air temperature with the same probability has reached 29.2 °C.

A similar increase is observed for maximum daily air temperature. In this case, the probability of hot days has increased by dozens of times. For example, the probability of an air temperature of 34 °C during 1961–1990 was about 0.03% (or even lower), whereas during 1995–2024 it reached about 0.8%. Thus, the probability increased by at least 27 times (Fig. 7b).

The maximum daily air temperature with a 0.1% probability was about 33.1 °C in the first period and 36.3 °C in the second period.

This indicates a significant increase in the probability of hot days. In particular, the likelihood

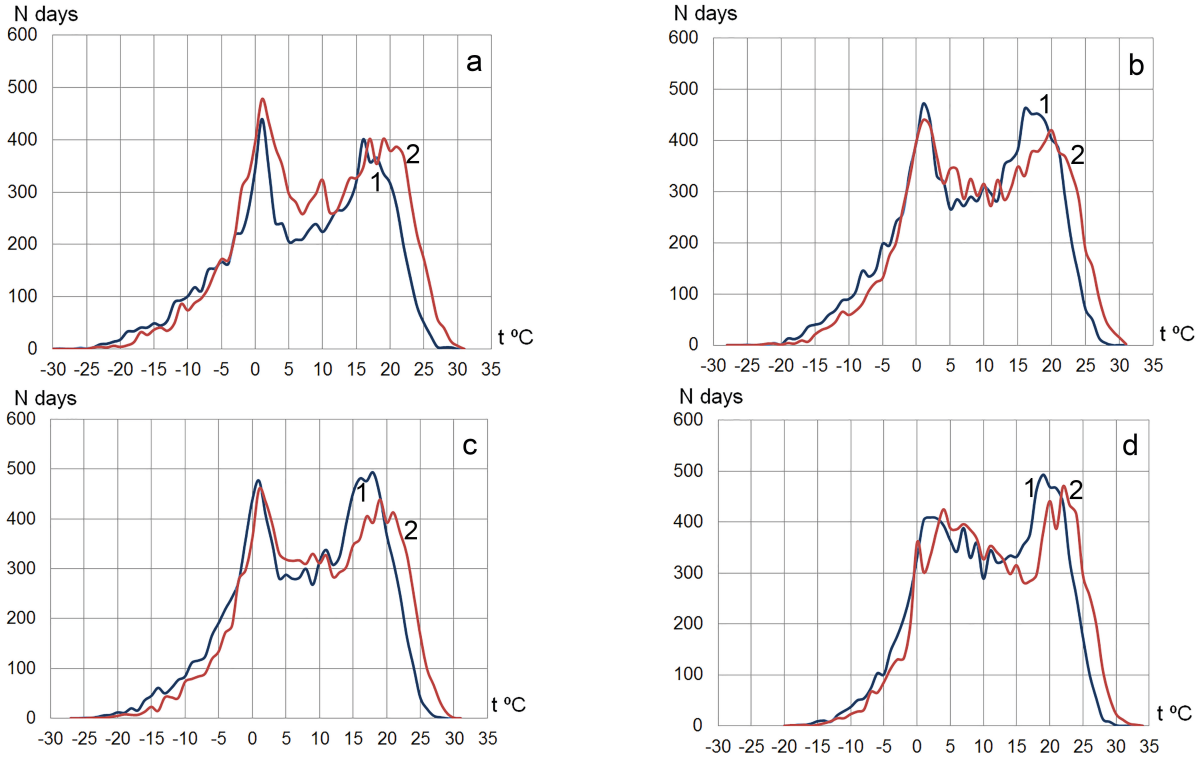


Fig. 4. Histograms of mean daily air temperature during 1961–1990 (1) and 1995–2024 (2) at meteorological stations, located in Ukraine: a – Konotop, b – Kyiv, c – Uman, d – Odesa

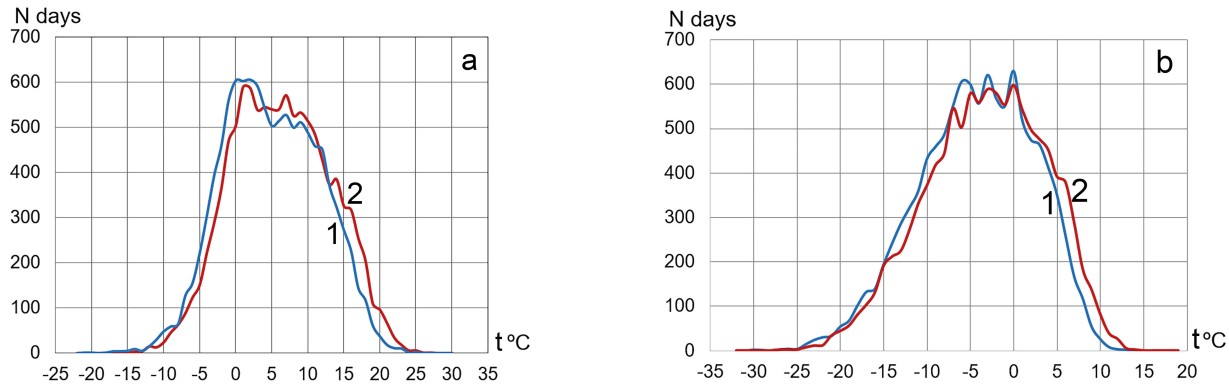


Fig. 5. Histograms of mean daily air temperature at meteorological stations Mont-Aigoual (a) and Zugspitze (b) during 1961–1990 (1) and 1995–2024 (2)

of days with mean daily temperature of 26 °C in Kyiv during 1995–2024 was approximately 10 times higher than during 1961–1990. An even larger difference (several dozen times) is observed for mean daily temperature above 27 °C.

During 1961–1990, there were 15 days in Kyiv with mean daily temperature in the range of 26.0–26.9 °C and 4 days in the range of 27.0–27.9 °C. Higher values were not observed. During the last 30 years (1995–2024), the number of such days increased several times: 97 days with temperature in the range of 26.0–26.9 °C, 55 days in the range of 27.0–27.9 °C, 29 days in the range of 28.0–28.9 °C, and 19 days with even higher temperature.

Heat waves as a component of climate change

Episodes of high temperature affecting relatively large territories are commonly referred to as heat waves. This phenomenon has been described in numerous publications (Boboc et al., 2025; Pekar et al., 2024; Shevchenko et al., 2020, 2022; Zschenderlein et al., 2019). In particular, several such events occurred in 2024. These heat waves can be visualized using the Ventusky platform (Fig. 8).

This figure shows rather common feature of spatial distribution of air temperature in the warmest period of year. The significant heat waves, which negatively impact on the health and even mortality is observed usually in the southern and in the south-eastern Europe.

On July 14, 2024, the air temperature in a few European regions reached 37–40 °C. For example, the air temperature in Bucharest reached 39.7 °C, in Kyiv it was 35.9 °C. According to the study (Ionita et al., 2025b), heatwave conditions in southern Romania persisted for 63 out of 92 days (68% of the summer), making 2024 one of the most prolonged and intense heatwave seasons on record.

4. DISCUSSION

The obtained results indicate that climate change in the studied region of Europe has several distinct features. The main one is the increase in air temperature. According to the data used in the study, the highest temperature increase is observed in the northern and the north-eastern parts of Ukraine. The available data can be compared with the results published in paper (Twardosz et al., 2021). At the Ukrainian stations, the air temperature trends during 1985–2020 were as follows: Konotop – increase by 0.84 °C/dec, Kyiv – increase by 0.83 °C/dec, Uman – increase by 0.81 °C/dec, and Odesa – increase by 0.78 °C/dec. At Helsinki station, the trend was lower – increase by 0.68 °C/dec. A much smaller increase (0.46 °C/dec) is observed at Bonn station. A similar result can be found in the above mentioned article (Twardosz et al., 2021), which shows that the increase in air temperature in the north-eastern part of Ukraine is considerably greater than in Western Europe.

Available data from meteorological stations located near Kyiv, indicate that a large city affects air temperature, suggesting an urban heat island effect. This urban impact is estimated to be about 0.5 °C (Vyshnevskyi et al., 2022). At the same time, this difference does not affect the total features of climate change, observed on the large territory.

More interesting is the change of daily air temperature. On the main territory of Europe, air temperature may drop below 0 °C. In such cases, the latent heat of water, released during freezing and absorbed during melting, plays a significant role in air temperature stabilizing. This is particularly important because water is always present in the atmosphere and often on the soil surface, as well as in water bodies, which frequently undergo freezing and melting.

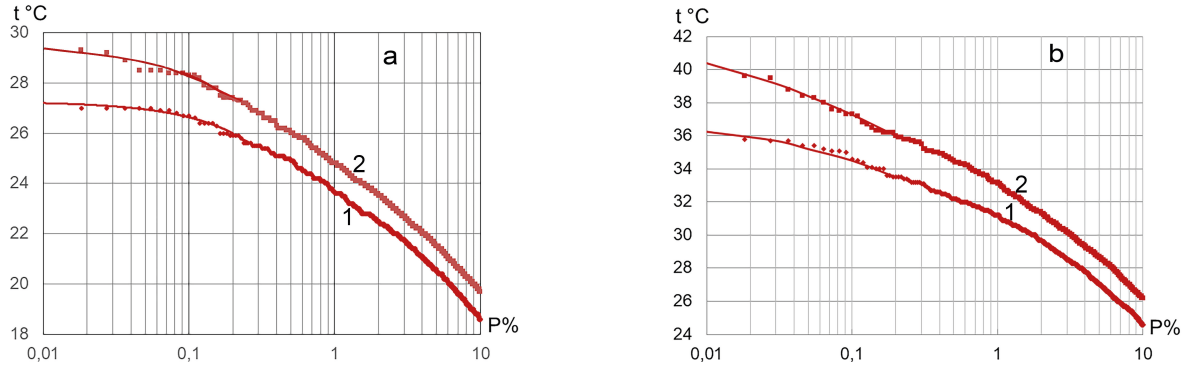


Fig. 6. The probability of mean (a) and maximum (b) daily air temperature at Bonn meteorological station during 1961–1990 (1) and 1995–2024 (2)

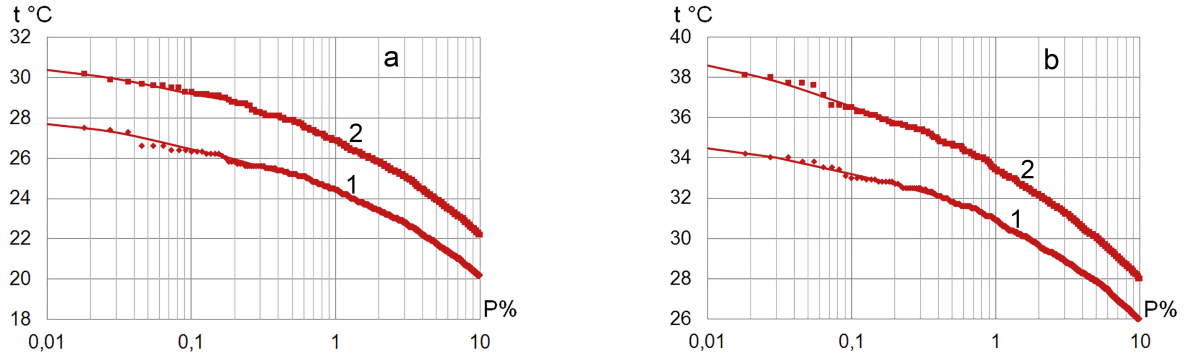


Fig. 7. The probability of mean (a) and maximum (b) daily air temperature at meteorological station Kyiv during 1961–1990 (1) and 1995–2024 (2)

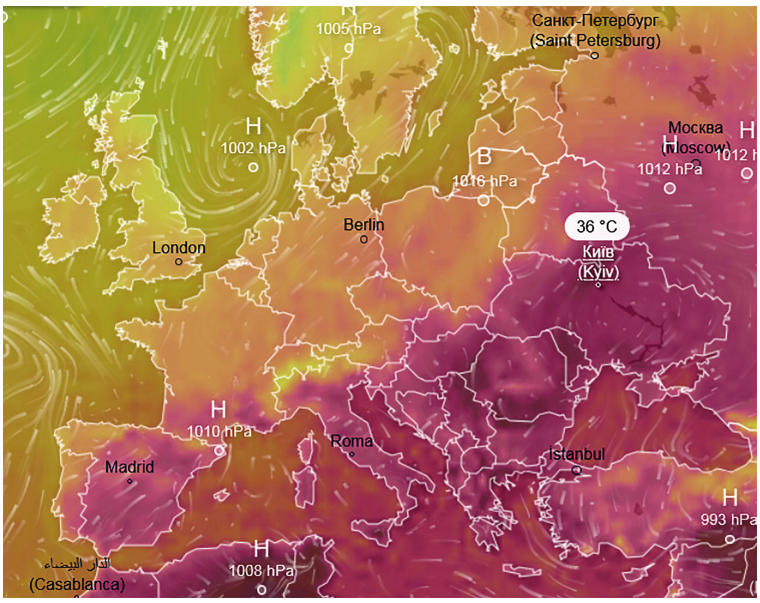


Fig. 8. The maximum daily temperature in Europe on July 14, 2024

For example, the freezing and melting of ice in the Baltic Sea near Helsinki results in a significant repeatability of air temperature around 0–2 °C. In contrast, in Odesa, where the sea very rarely freezes, this peak is much less pronounced. Such feature of weak peak is observed in mild climate of the Western and the Southern Europe, where temperature below 0 °C is uncommon (e.g., Bonn).

The air temperature characteristics in mountainous regions, as described in the article (Pekar et al., 2024), are also noteworthy. Low temperature and persistent snow cover result in a high frequency of temperature about 0 °C. At significant altitudes, relatively high temperature are rare, and that is why bimodality is not observed. The data from two stations Mont-Aigoual and Zugspitze show this feature.

This phenomenon can be explained not only by the presence of water in the atmosphere, but also by the frequent presence of water or ice on the ground surface.

Importantly, the latent heat of melting (or freezing) of water is very high, amounting to 334 kJ kg^{-1}. This value is significantly greater than the specific heat capacity of water (4.18 kJ kg^{-1} $°C^{-1}$) (Pekar et al., 2024; Schröder & Gawron, 1981). Thus, the energy required to melt 1 kg of ice at 0 °C is nearly 80 times greater than that needed to increase the temperature of 1 kg of water by 1 °C. This large energy exchange during phase transitions, together with the high heat capacity of water, contributes to the stabilizing effect of water on air temperature.

It should be noted that the left peak of the recurrence of mean daily air temperature does not coincide exactly with the melting point of ice or the freezing point of water. The main reason for this discrepancy is the difference between air temperature at the soil surface and that measured at the standard height of 2 m. This is evident from observational data at two Ukrainian stations: Kyiv and Uman (Fig. 9).

The analysis of Figure 9 shows that under winter conditions, the air temperature exceeds the surface temperature by about 1 °C. When the surface temperature is 0 °C, the air temperature at a height of 2 m is approximately 1 °C.

It should be noted that the accuracy of surface temperature measurements in Ukraine is ±1 °C; therefore, a small error in the presented relationship is possible.

The presented data suggest that the recurrence of mean daily air temperature differs significantly between the cold and warm seasons. To verify this assumption, the available data from Kyiv station were divided into two periods: the cold season (five months, from November 1 to March 31) and the warm season (five months, from May 1 to September 30). The transitional months (April and October) were not considered. The obtained results are shown in Figure 10.

As shown in Figure 10, the shapes of the curves representing the frequency distribution of mean daily air temperature in cold and warm seasons are very

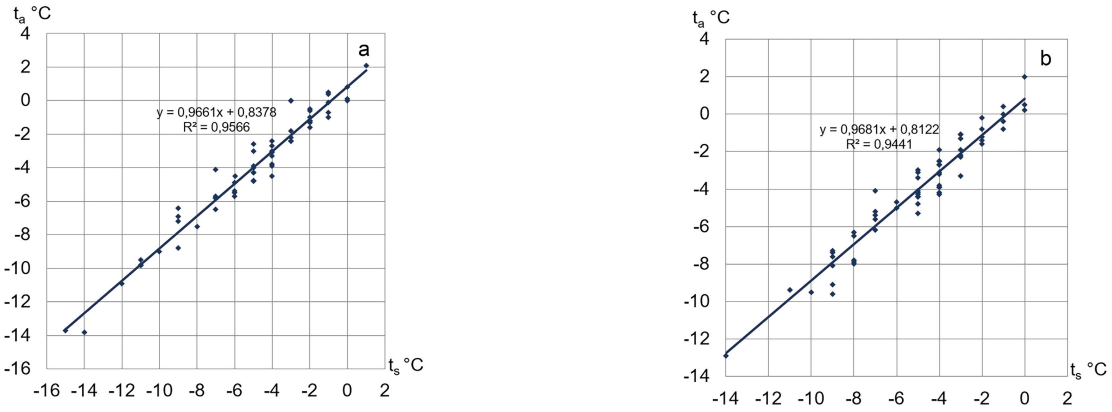


Fig. 9. The dependence of mean monthly air temperature (ta) and mean monthly surface temperature (ts) in Kyiv (a) and Uman (b) during a few winters of 1991–2024

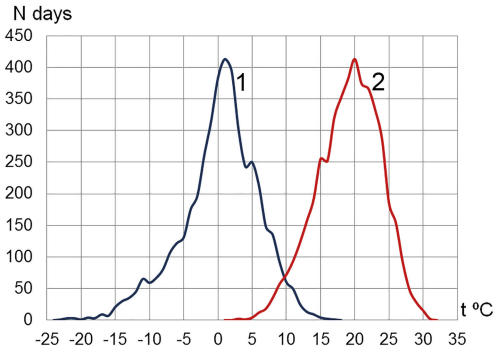


Fig. 10. Histograms of mean daily air temperature at Kyiv meteorological station during 1995–2024: 1 – from November 1st till March 31, 2 – from May 1st till September 30

similar. In both cases, the left tail of the distribution is longer than the right one. This feature is more pronounced for the cold season.

This asymmetry indicates that the mean air temperature in the cold season is lower than the temperature corresponding to the highest frequency, which lies within the 0–2 °C range. Indeed, the mean air temperature of the cold season (November 1 to March 31) in Kyiv is minus 0.2 °C. A similar pattern is observed for the warm season (May 1 to September 30): the temperature with the highest frequency is around 20 °C, whereas the mean air temperature during this period is 18.6 °C.

Interestingly, the lowest frequency of air temperature occurs in the 9–10 °C range, which coincides with the mean temperature of the two studied seasons (9.2 °C) and is close to the mean annual temperature.

These results suggest that the distribution of mean daily air temperature at Kyiv meteorological station (and elsewhere) can be interpreted as a combination of two similar seasonal distributions corresponding to the cold and warm periods.

Similar patterns are observed in Northern Europe, as evidenced by data from Helsinki station. In contrast, at Bonn station, located in the temperate climate of Western Europe, the peak in the 0–2 °C range is absent. Nevertheless, bimodality is present in both cases: it is very pronounced at Helsinki and much less distinct at Bonn.

5. CONLUSIONS

Climate change in Europe, and particularly in Ukraine, exhibits several distinctive features. Since the beginning of meteorological observations in the late 19th century, the mean annual air temperature in Ukraine has increased by more than 3 °C. Available observational data indicate that increase in air temperature in Western Europe and in mountainous regions is smaller than that observed across most of Ukraine.

A common feature of recent climate change is the acceleration of air temperature increase over the past decades.

A characteristic feature of the mean daily air temperature distribution, especially in Eastern Europe, is bimodality. The first mode, with high frequency, corresponds to air temperature in the range of 0–2 °C. This feature can be explained by the substantial latent heat associated with the melting and freezing of water which present in the atmosphere and on the land surface.

The second (right-hand) mode corresponds to higher temperature, the exact value of which depends on the region and elevation. In a cool climate (e.g., Helsinki), the second mode typically falls within the range of 10–15 °C. Higher values of the right-hand peak (15–20 °C) are characteristic of Ukraine, located predominantly in the south-eastern part of Europe.

In mountainous regions, bimodality is less pronounced than in lowland areas.

A comparison of air temperature distributions for the two periods (1961–1990 and 1995–2024) indicates that the increase in temperature associated with low exceedance probabilities (0.1% or 1%) is substantially greater than the increase observed at higher probabilities. As a result, the probability of hot days during the period 1995–2024 has become significantly higher compared with 1961–1990.

Conflict of interest

The author declares that he has no competing interests.

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