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Unraveling seasonal surface air temperature trends in Ukraine (1990—2021)

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This study examines the spatial and temporal characteristics of surface air temperature (SAT) changes in Ukraine from 1990 to 2021. It focuses on the seasonal and regional variabilities, long-term trends, the harmonic characteristics of the annual temperature cycle, and their implications for regional climate change.

From meteorological observations at 93 weather stations (Ω_{93} dataset), the average annual SAT was 9.6±0.8 °C. Over the past three decades, the mean rate of temperature increase reached a significant +0.64± 0.01 °C per decade, substantially exceeding historical averages. This warming trend is further evidenced by annual temperature anomalies, which showed only three years (1993, 1996, and 1997) with negative anomalies (ranging from –0.32 to –0.55 °C), while the remaining years were anomalously warm, with peaks in 2007, 2015, 2019, and 2020 (reaching up to +2.79 °C).

Monthly SAT trends revealed statistically significant warming across nearly all months, ranging from +0.34°C to +1.19 °C per decade. The most intensive warming was observed in December (+1.19±0.14 °C per decade), particularly in northern and eastern Ukraine. Conversely, January exhibited minimal or even negative trends in many regions, except for Crimea and southern Ukraine, where moderate warming persisted.

The amplitude and phase of seasonal SAT variations are reliable indicators of continental climate characteristics. In 1990—2021, the mean amplitude of the seasonal temperature cycle was 12.3 ± 1.0 °C, with a decreasing trend of approximately 0.1 °C per decade. This decline is largely attributed to warming during the warm season. The mean phase of the seasonal cycle was estimated at 1.29 ± 0.06 months. A slight phase shift of –0.012 months per decade was also observed over the study period.

The study highlights increased temperature variability during winter and spring months, contributing to a more comprehensive understanding of contemporary climate shifts in Ukraine. These findings underscore the urgent need for adaptive strategies to mitigate the impacts of ongoing climate change.

Key words: climate change, seasonal surface air temperature trends, temperature anomalies, amplitude and phase of seasonal temperature variations.

Introduction. Surface air temperature (SAT) changes are a key indicator for evaluating global warming and its effects on specific regions. SAT trends provide valuable insights into the rate and magnitude of climate change over time and are crucial to climate monitoring efforts. On a global scale, the average temperature has risen by about 1.1 °C since the late 1800s, with most of this increase occurring after the 1970s [Song et al., 2022]. In recent years, temperatures have reached unprecedented levels, with the 2010s being

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the hottest decade recorded [Robinson et al., 2021; Heeter et al., 2023].

SAT trends are more prominent in the Northern Hemisphere, where the predominance of land accelerates warming compared to the ocean-dominated Southern Hemisphere. The global average annual surface temperature variations correlated strongly with fluctuations in the predominant atmospheric circulation type [Olmo et al., 2020]. Regions such as Europe, Asia, and North America exhibit pronounced warming trends, particularly in highly urbanized and industrialized areas [Perkins-Kirkpatrick, Lewis, 2020; Shen et al., 2022]. Over the past several decades, temperature trends in the Northern Hemisphere have been a major focus of climate research. Scientists from various nations and organizations have contributed to this expanding field, advancing techniques and integrating observational data with climate modelling [IPCC, 2023]. Research consistently highlights a notable rise in average air temperatures across the Northern Hemisphere over the past century, with the most significant increases occurring since the mid-20th century [Manabe, 2011; Heeter et al., 2023; Cao et al., 2023].

Therefore, climate change remains one of the key global challenges of the 21st century, significantly impacting ecosystems and socio-economic processes worldwide [Abbass et al., 2022; Parmesan et al., 2022]. Ukraine, located in a temperate climate zone, is no exception to these challenges [Lipinskyi et al., 2003]. Over the past 50 years, observations have consistently shown a steadily increasing average annual air temperature [Wilson et al., 2021; Boychenko, Maidanovych, 2024]. This process is accompanied by changes in the structure of precipitation, an increase in the frequency of extreme climatic events such as droughts, downpours, and heat waves, which is confirmed by research [Boychenko et al., 2016, 2025; Vozhegova et al., 2021; Karamushka et al., 2022].

According to the latest results from climate models, by the end of the 21st century, the average temperature in Ukraine is expected to increase by 2.5—3.0 °C, depending on the greenhouse gas emissions scenario [Krakovska, 2018; IPCC, 2023]. This temperature trend could lead to significant changes in agriculture, water resources, biodiversity, and public health [IPCC, 2023]. For example, studies on the impact of temperature changes on the agricultural sector suggest the need to adapt crop-growing technologies to new climatic conditions [Mahato, 2014; Malhi et al., 2021]. The southern regions of Ukraine are particularly vulnerable, with an already increasing risk of desertification and a decline in yields [Vozhegova et al., 2020; Pichura et al., 2022].

Climate change, both on global and regional scales, intensified significantly in the second half of the 20th century and especially in the first decades of the 21st century [Olonscheck et al., 2021; IPCC, 2023]. Analysis of records from 45 weather stations indicates that, during the 1991—2020 climatic baseline, Ukraine exhibited a statistically significant increase in mean annual SAT, amounting to 0.79±0.08 °C per decade [Boychenko, Maidanovych, 2024].

This article aims to comprehensively analyze recent changes in Ukraine's temperature regime by examining SAT trends over the past few decades using weather observations. Specifically, we analyzed: average annual SAT changes, the linear trend, anomalies, spatial distribution, and annual cycle; changes in, and linear trends of, the amplitude and phase of SAT; seasonal variation of the temperature root-mean-square errors and differences in linear trends; spatial distributions of monthly SAT trends for each calendar month.

This study builds on the authors' previously published primary results [Boychenko, Maidanovych, 2024], offering a more in-depth analysis using updated observational data.

Data and methods. This research is based on the analysis of changes in average annual and monthly surface air temperature (SAT) across Ukraine. The data included information from 93 meteorological stations (Ω_{93} dataset) for the period 1990—2021 (Fig. 1) obtained from the Central Geophysical Observatory of Ukraine and open climate data sources [Open Data-Server, 2023; Climate Explorer, 2023; Weather and Climate, 2023].

The dataset underwent comprehensive quality control. To evaluate the reliability of the time series, the homogeneity record was tested using a model developed by the authors specifically for this purpose. The procedure also included the detection and removal of evident errors and outliers by cross-checking with station metadata. This approach reveals potential breaks or shifts in the data while preserving the original climatic signal and the natural variability of the series, ensuring that subsequent analyses were not biased by artificial corrections.

Although modern homogenization tools such as Climatol (https://www.climatol.eu/) are widely applied in climate data analysis, their full implementation may not always reflect reality. Such procedures tend to smooth or artificially adjust the data, potentially diminishing the representation of true climatic extremes and regional features. For this reason, in the present study, we adopted our own verification approach, which ensures adequate data quality while maintaining the authenticity of the climatic variability inherent in the observational records.

The selection criteria for meteorological stations included an even spatial distribution across Ukraine and elevation levels not exceeding 350—400 meters above sea level. It is essential to evaluate the temperature changes observed in mountainous and foothill regions separately, as altitude significantly affects meteorological parameters (e.g., a vertical temperature gradient), which can potentially skew aggregated estimates. According to [Boychenko, Maidanovych, 2023], the annual altitudinal temperature gradient in Ukraine during 1991—2020 is estimated at –0.60 ± 0.22 °C per 100 m. These gradient exhibits notable seasonal variability, with the highest values observed in July—August (–0.63 to –0.73 °C/100 m) and the lowest in April—May (–0.45 to –0.55 °C/100 m).

The distribution of the meteorological stations used in this study is shown in Fig. 1.

Unfortunately, due to the war in Ukraine, meteorological data from parts of the eastern regions have been unavailable since 2014.

We analyzed the spatial and temporal distribution of annual and seasonal SATs from 1990 to 2021. The seasonal temperature cycle

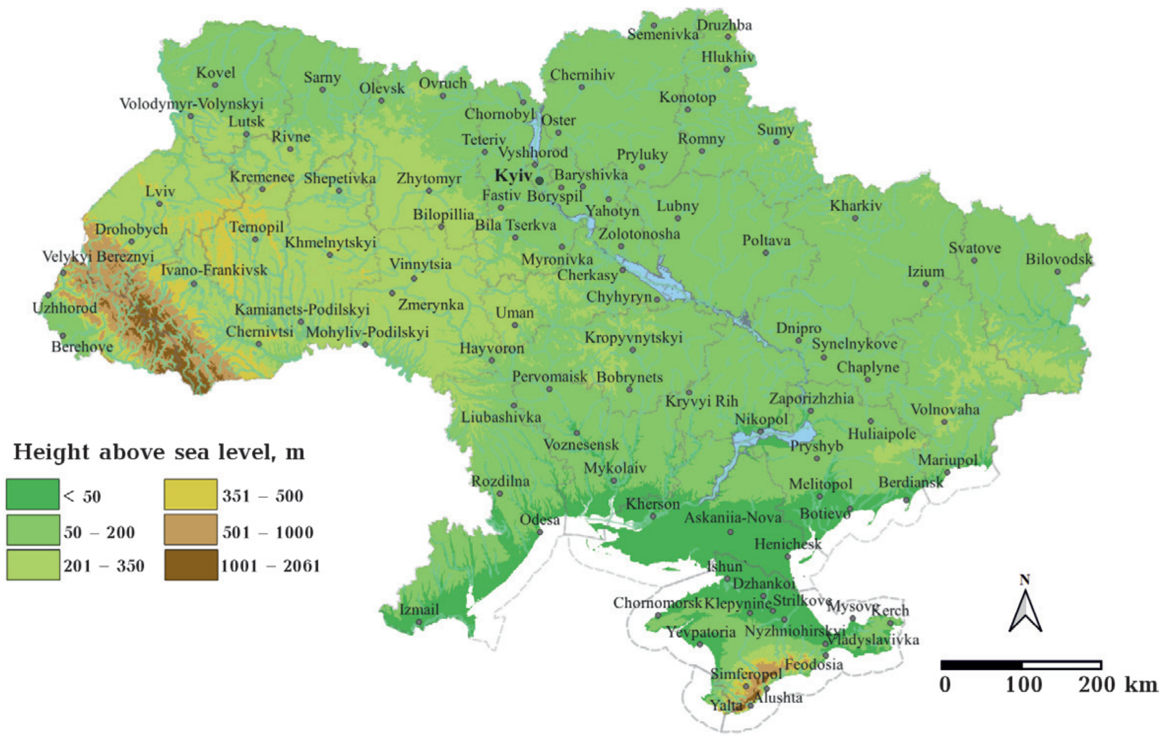

Fig. 1. Locations of the meteorological stations used in the study.

was approximated using Fourier analysis with a single harmonic, allowing an objective estimation of the annual amplitude of temperature variation [Von Storch, Zwiers, 1999].

Climatic norms for 1961—1990 were sourced from the Climate Cadastre of Ukraine [2005]. Seasonal temperature trend analysis involved calculating linear trend coefficients for each calendar month at each station, followed by spatial averaging. Linear trends were computed using the method of least squares.

Anomalies for specific variables and years were calculated as the differences between the observed annual values and the corresponding climatic norms or multiannual averages [State of the Global Climate, 2021; Climate Bulletin, 2024]. In our research, SAT anomalies ΔT were computed by subtracting the 1961—1990 climatic baseline T_{nrm} from the annual mean values T_{year} of the Ω_{93} dataset:

$$\Delta T = T_{\text{year}} - T_{\text{nrm}}\,;\; T_{\text{nrm}} = 8.4\ ^\circ\text{C}\,. \qquad (1)$$

The annual temperature cycle is well approximated by a single-harmonic Fourier fit [Climate Bulletin, 2024; Boychenko, Maidanovych, 2024]. The fitted equation is:

$$T_{\text{m}} = T_{\text{year}} + a\sin\left(\frac{2\pi(m-0.5)}{12}\right) + b\cos\left(\frac{2\pi(m-0.5)}{12}\right),$$

$$T_{\text{year}} = \frac{1}{12}\sum T_m\,,$$

$$a = 1/6\sum T_{\text{m}}\sin\frac{2\pi(m-0.5)}{12}\,,$$

$$b = 1/6\sum T_{\text{m}}\cos\frac{2\pi(m-0.5)}{12}\,,$$

$$A = \sqrt{a^2+b^2}\,,\; F = \text{arctg}\frac{b}{a}\,, \qquad (2)$$

where T_m is the monthly mean temperature of month m (m=1,…,12), °C; T_{year} is average annual temperature, A is the amplitude (°C); F is the phase (in months), a and b are approximation constants.

The Mann-Kendall test was applied to evaluate the statistical significance of trends at the 95 % confidence level. This nonparametric method is widely used to detect monotonic trends in climate time series, as it determines whether a variable shows a consistent increasing or decreasing pattern over time without assuming any specific data distribution. Statistical processing followed established methods for climate data analysis [von Storch, Zwiers, 1999] and was conducted using Microsoft Excel with the XLSTAT software package.

To create thematic maps, we used the GADM database of global administrative areas. Climate data interpolation was performed in SAGA GIS (System for Automated Geoscientific Analyses) using the radial basis function with thin plate spline interpolation [Böhner et al., 2006]. This method provides an accurate and efficient approach for interpolating point-based temperature data across space [Hutchinson, 1991; Boer et al., 2001; Hancock, Hutchinson, 2006]. Final visualization and map production were carried out using QGIS [Passy, Théry, 2018]. To avoid local distortions of climatic trends, the Carpathian region (elevations above 400 m) was excluded, and the detailed orographic features of the Crimean Mountains were disregarded during the spatial interpolation and data visualization on small-scale maps.

Average monthly SAT anomalies for the period 1990—2021 were calculated by subtracting the corresponding monthly climatic norms for 1961—1990.

Results. ***Average annual surface air temperature changes in Ukraine (1990—2021).*** According to an analysis of meteorological data from the Ω_{93} weather dataset, the average annual SAT in Ukraine for the climatic norm period 1991—2020 was 9.6 ± 0.8 °C, compared to the climatic norm of 8.4 ± 1.1 °C for 1961—1990. For the period 1990—2021, the average annual SAT in Ukraine was 9.6±0.8 °C also, with a statistically significant increase of 0.64±0.01 °C per decade (Fig. 2).

For this study, the Mann-Kendall trend test was applied to assess monotonic trends in surface air temperature. The analysis yielded Kendall's tau values ranging from 0.373 to 0.590, indicating predominantly strong positive correlations in the time series data. The p-

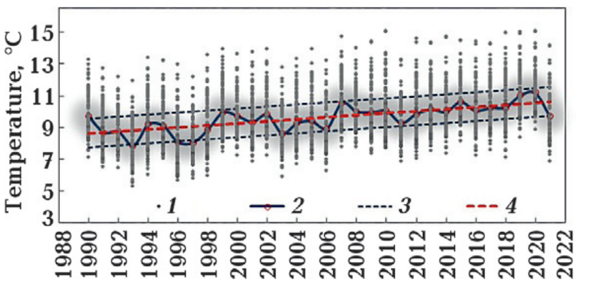

Fig. 2. Average annual SAT in Ukraine for 1990—2021: *1* — time series from 93 weather stations, *2* — averaged time series, *3* — ±σ, *4* — linear trend.

values were consistently <0.0001, which is far below the chosen significance level (α=0.05).

Because the p-values are substantially lower than α, the null hypothesis (H_0: no trend in the series) is rejected in favour of the alternative hypothesis (H_a: a trend exists in the series). This provides strong statistical evidence of significant monotonic trends across most stations. The probability of incorrectly rejecting the null hypothesis while it is true (type I error) was estimated to be less than 0.01 % for approximately 94 % of stations. At several stations, including Uzhhorod, Rivne, Izmail, and Velykyi Bereznyi, the error probability ranged between 0.05 % and 0.28 %, which still supports the robustness and reliability of the findings. Overall, the results confirm statistically significant upward trends in SAT across most of Ukraine, providing clear evidence of long-term warming processes in the region.

The average annual SAT anomalies for 1990—2021 show that colder-than-average years occurred only in 1993, 1996, and 1997 (Δ*T* ranging from –0.55 to –0.32 °C), whereas warmer-than-average years dominated the rest of the period. The warmest years included 2007, 2015, 2019, and 2020 (Δ*T* ranging from +0.23 to +2.79 °C), as illustrated in Fig. 3.

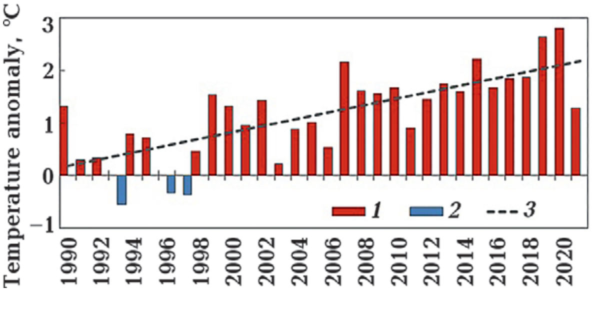

Fig. 3. Average annual SAT anomalies in Ukraine for 1990—2021: *1* — cold anomalies, *2* — warm anomalies, *3* — linear trend.

For example, the year 2007 was particularly anomalous, not only in Ukraine but across many regions globally [Busuioc et al., 2007; Kundzewicz et al., 2009; Founda, Giannakopoulos, 2009]. In Ukraine, the annual average SAT in 2007 was 2—3 °C above the climatic norm. During the summer, most of the country (especially southern regions and Crimea) experienced extreme heat (up to 2—6 °C above the norm), whereas in the northern regions, temperatures remained near average. Unusually high temperatures were also recorded in January and March (3—8 °C above the norm, depending on the region), while April and November saw abnormally low SAT values, 1—3 °C below the norm, particularly in Transcarpathia and Crimea.

The spatial distribution of average annual SAT and its corresponding trends from 1990 to 2021 are presented in Fig. 4.

As shown in Fig. 4, *a*, the average annual SAT over 1990—2021 ranged from around 7 °C in northeastern Ukraine to 11—12 °C in southern regions, maintaining a clear latitudinal gradient. Meanwhile, SAT trends revealed a northwest-southeast gradient of increasing values (Fig. 4, *b*), with pronounced warming hotspots in urbanized, industrialized, and microclimatically distinct areas, where rates reached +0.7…+0.8 °C per decade. This accelerated warming toward higher latitudes within Ukraine reflects a broader hemispheric pattern observed in the Northern Hemisphere [Boychenko, 2008].

Some discrepancies may be attributed to the inclusion of a larger number of meteorological stations in this study, particularly those in southern regions and Crimea. Similar assessments of temperature changes in southern regions and Crimea have been reported in recent studies [Boychenko et al., 2022; Karamushka et al., 2022].

Annual cycle of surface air temperature in Ukraine. SAT seasonal variation is typical for temperate latitudes [Lipinskyi et al., 2003]. In recent decades, maximum temperatures have

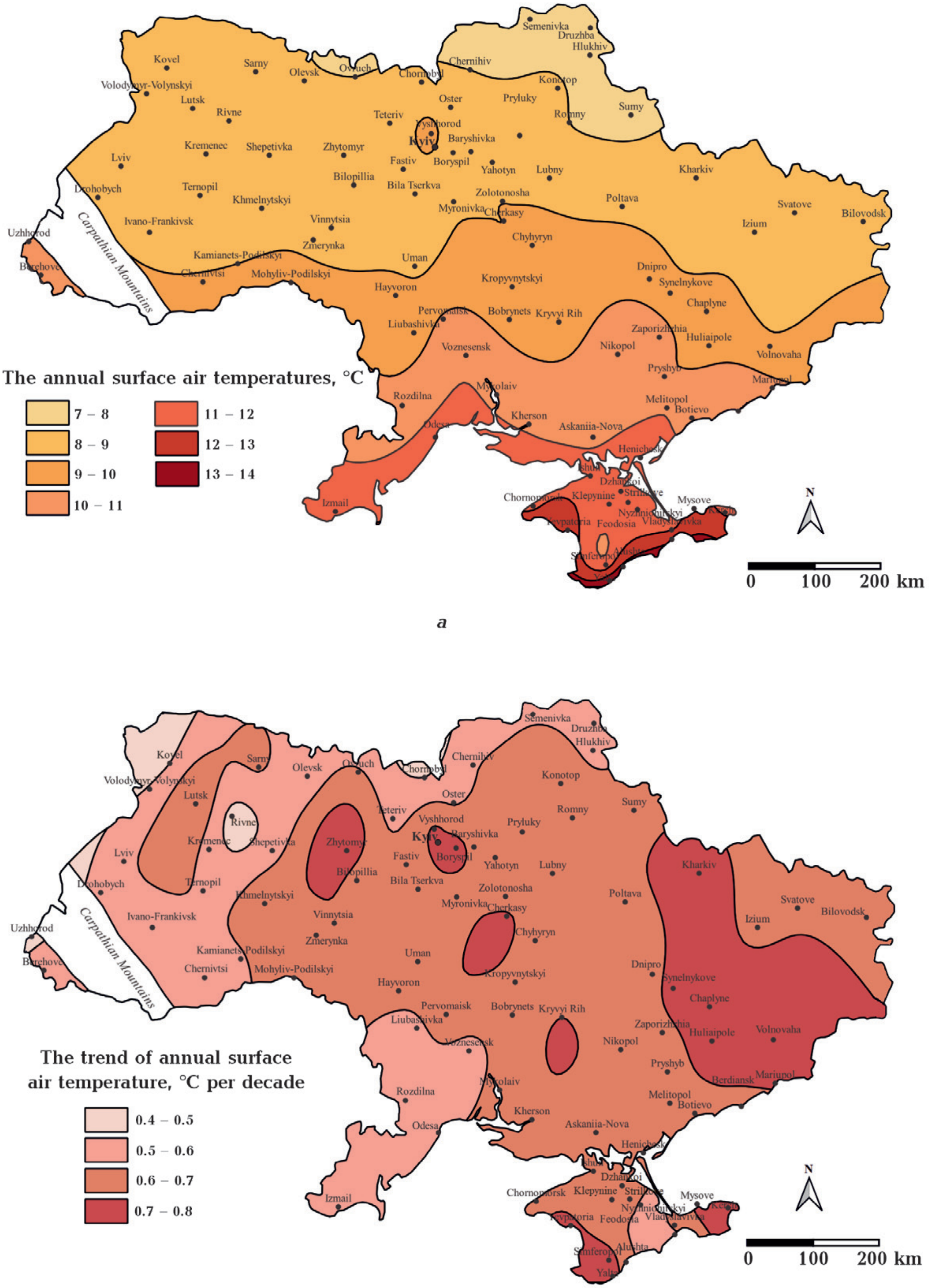

Fig. 4. Spatial distribution of average annual SAT (*a*) and corresponding trends (*b*) in Ukraine, 1990—2021 (*a* — SAT averages, *b* — SAT trend per decade).

generally occurred during the summer, ranging from +19.6 to +21.8 °C, while minimum temperatures are recorded in winter, ranging from –2.4 to –0.8 °C. During transitional seasons, average temperatures range from +3.0 to +15.6 °C in spring and from +3.7 to +15.5 °C in autumn.

The annual temperature cycle is well approximated by a single-harmonic Fourier fit (2), which effectively captures the primary seasonal variability (parameters of equation (2) are a_1=–3.38 and b_1=–11.79). The quality of the approximation is high, with the coefficient of determination (R^2) ranging from 0.97 to 0.99, depending on the region and the length of the observation series [Climate Bulletin, 2024; Boychenko, Maidanovych, 2024]. Therefore, most of the variance in monthly mean temperatures is explained by the first harmonic component, corresponding to the dominant annual cycle.

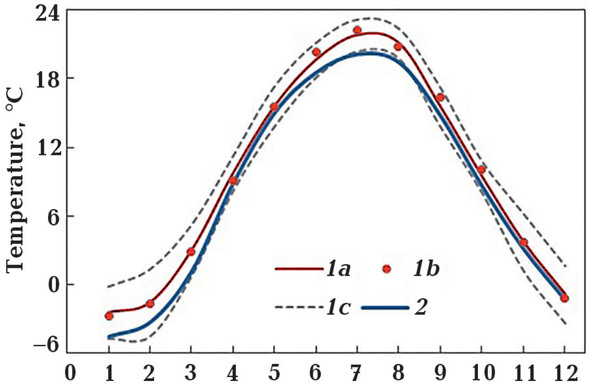

Fig. 5. Annual cycle of SAT in Ukraine for 1990—2021: *1a* — averaged monthly SAT (Ω_{93}), *1b* — Fourier approximation (2), *1c* — ±σ, *2* — climate norm (1961—1990).

A comparison of the average monthly SAT for 1990—2021 (Ω_{93} dataset) with the climate norm for 1961—1990 is shown in Fig. 5. The most significant warming has occurred during the months of January—April and June—August.

The amplitude (*A*) and phase (*F*) of the first harmonic of seasonal SAT variations are reliable indicators of continental climatic effects. Based on Fourier analysis, the average temperature amplitude in Ukraine for 1990—2021 is 12.3 ± 1.0 °C, with a decreasing trend of ~0.1 °C per decade, primarily due to warming in the warm season [Boychenko, Maidanovych, 2024]. Changes in seasonal amplitude across Ukraine are presented in Fig. 6.

The phase (*F*) of the seasonal SAT cycle averaged 1.29 ± 0.06 months. The phase has shifted slightly by –0.012 months per decade (1990—2021), as shown in Fig. 7.

The interannual variability of SAT was assessed using the root-mean-square error (*s*) [Feng et al., 2003]. In recent decades, peak

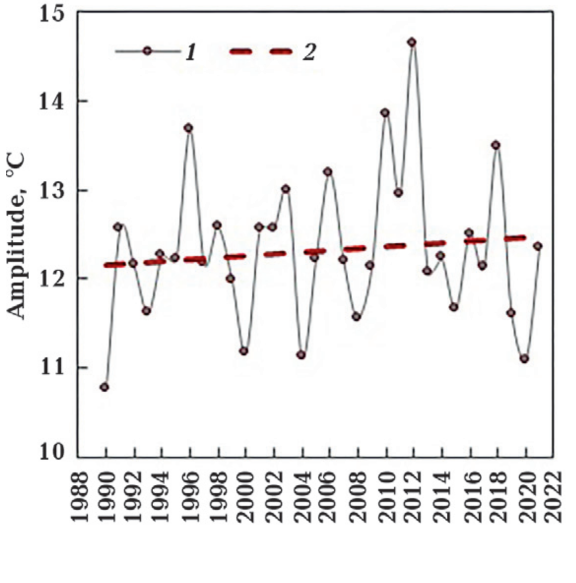

Fig. 6. The amplitude of the seasonal cycle of SAT (*1*) and linear trends (*2*) in Ukraine (1990—2021).

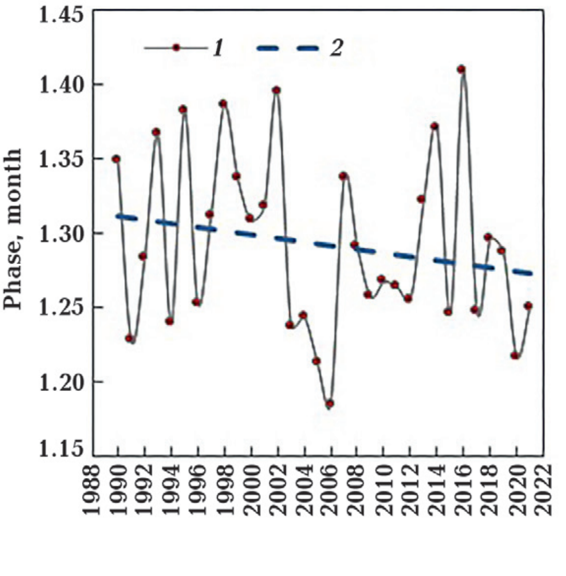

Fig. 7. The phase of the seasonal cycle of SAT (*1*) and linear trends (*2*) in Ukraine (1990—2021).

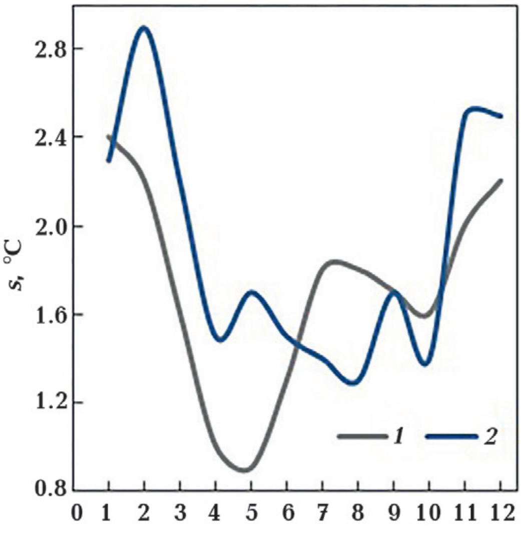

Fig. 8. The seasonal cycle of SAT root-mean-square errors in Ukraine: *1* — climate norm 1961—1990, *2* — average values for Ω_{93} dataset, 1990—2021.

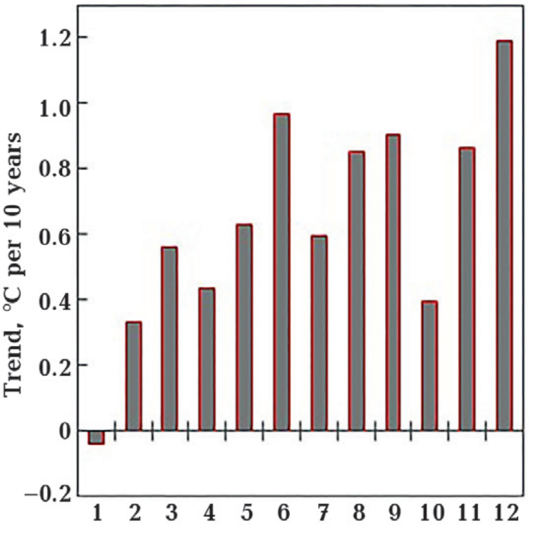

Fig. 9. The seasonal cycle of SAT linear trends in Ukraine (1990—2021).

variability (s=2.3÷3.0 °C) has occurred in the cold season (especially January—February), whereas minimum variability (s=1.3÷1.5 °C) is typical for summer. A comparison of seasonal variability between the periods 1961—1990 and 1990—2021 is shown in Fig. 8. Variability increased during winter and spring and decreased in summer, especially in March—May and June—August.

Linear trend analysis over the last three decades shows monthly SAT trends ranging from +0.34 to +1.19 °C per decade. An exception is January, where a slight cooling trend of –0.04 °C per decade is observed across most of Ukraine, excluding southern regions and Crimea. Conversely, December exhibits a strong warming trend of +1.19 ± 0.14 °C per decade, as illustrated in Fig. 9.

Winter. Mild and snow-deficient winters have become the norm in Ukraine, particularly in recent decades. The average monthly surface air temperatures for December, January, and February, averaged across the country for the period 1990—2021, are –0.8 ± 2.0 °C, –2.4 ± 1.9 °C, and –1.5 ± 1.8 °C, respectively.

The spatial distribution of trends in average monthly SAT during winter exhibits noticeable zonal differences. December shows the most pronounced warming, with trends ranging from +1.19 ± 0.14 °C per decade, especially in the northern, northeastern, and eastern regions (Fig. 10, December). In contrast, in January, there is an overall weak warming or even cooling trend, averaging –0.04 ± 0.32 °C per decade across most of Ukraine. Notable cooling trends were recorded at weather stations such as Oster (–0.60 °C per decade), Rivne (–0.58 °C per decade), Chernihiv (–0.44 °C per decade), and Druzhba (–0.41 °C per decade). However, southern regions, Crimea, and Zakarpattia show weak warming trends in January, ranging from +0.3 to +0.7 °C per decade (Fig. 10, January). In February, warming trends are evident but less intense compared to December. The SAT trends vary from +0.06 to +0.61 °C per decade across most regions. Yet, some stations in the northern part of the country display insignificant warming or even slight cooling, with trends from –0.02 to –0.26 °C per decade, as observed in Olevsk, Oster, Rivne, Ternopil, and Teteriv.

The trends of winter temperatures and the anomalously warm or cold months over 1990—2021 are presented in Fig. 11 and Table. While warm winters have become increasingly frequent in recent decades, the warmest winters occurred in December (2007,

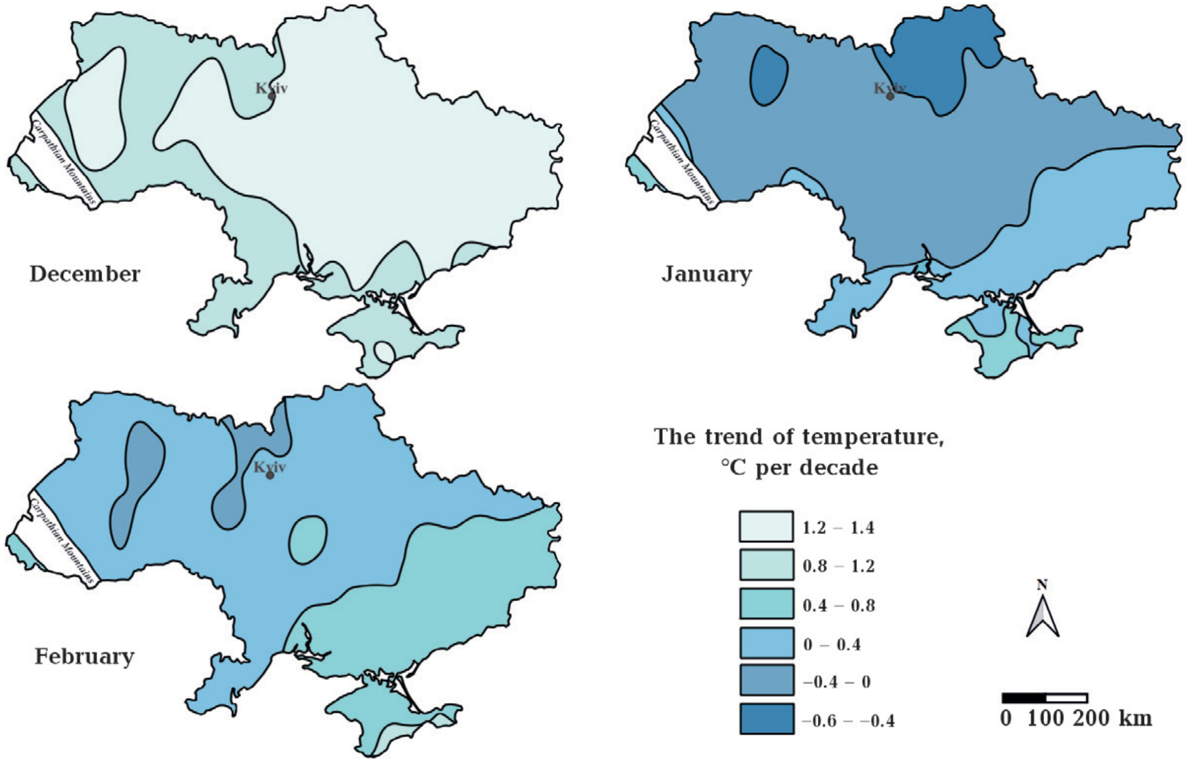

Fig. 10. Spatial distribution of monthly SAT trends in December, January, and February in Ukraine (1990—2021).

2015, 2019, 2020), January (1994, 2007, 2020), and February (1990, 2002, 2016), whereas the coldest ones were recorded in December (1993, 1996, 1997), January (1996, 2006, 2010), and February (1996, 2003, 2012).

Spring. In the context of climate change, spring has begun to arrive more rapidly and without delay in Ukraine in recent decades. The average monthly surface air temperatures for March, April, and May, averaged across

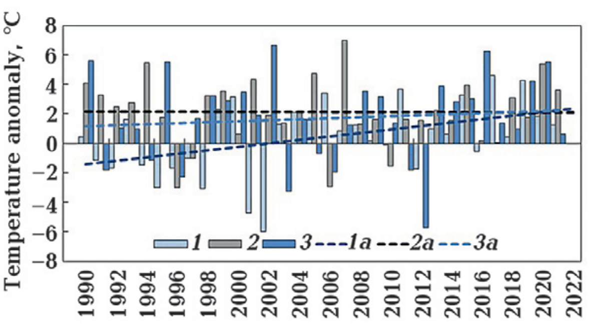

Fig. 11. Monthly SAT anomalies in Ukraine for 1990—2021: *1* — December; *2* — January; *3* — February; *1a*, *2a*, *3a* — respective linear trends.

the country, are 3.0 ± 1.4 °C, 9.8 ± 0.7 °C, and 15.6 ± 0.9 °C, respectively.

The spatial distribution of temperature trends in spring exhibits regional variability. In March, significant warming trends are observed across most of Ukraine, with a national average of +0.56 ± 0.13 °C per decade, and even higher values (up to +0.93 °C per decade) in the southern regions and Crimea (Fig. 12, March). In April, the overall warming trend remains at approximately +0.56 ± 0.13 °C per decade. However, the spatial pattern shifts: western and central Ukraine exhibit the highest warming, while the southeastern, northeastern, and southern regions show weaker trends, ranging from +0.10 to +0.43 °C per decade (Fig. 12, April). May demonstrates the most pronounced warming among the spring months, with an average trend of +0.63 ± 0.23 °C per decade. Particularly strong trends are recorded in the eastern and southern regions, with values between +0.8 and +1.0 °C per decade. However, negative trends are also detected in the Transcarpathian region, notably at stations such as

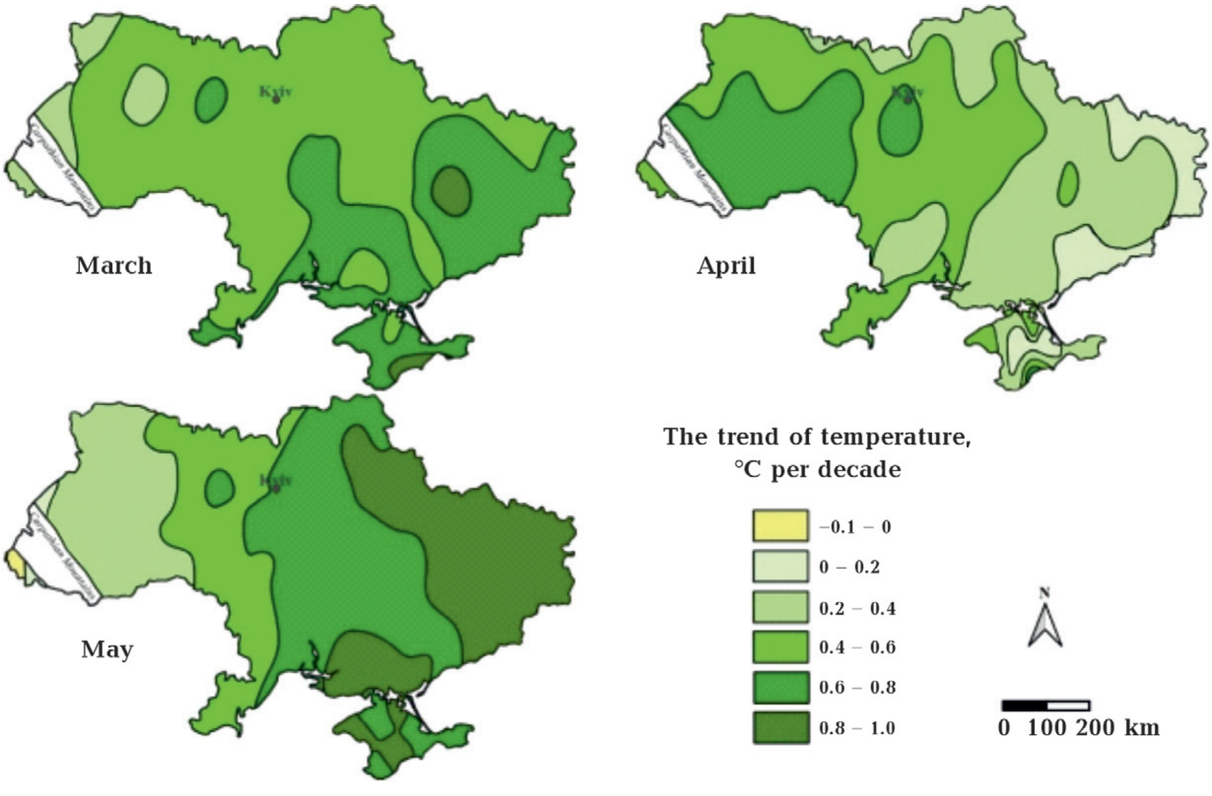

Fig. 12. Spatial distribution of monthly SAT trends in March, April, and May in Ukraine (1990—2021).

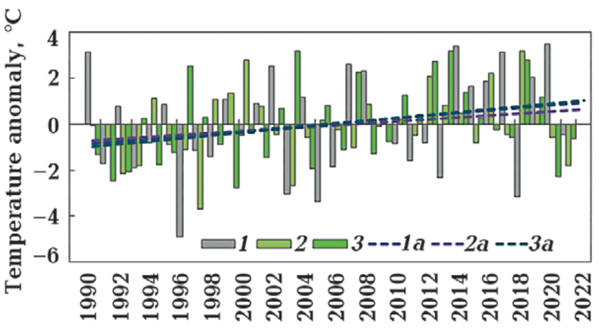

Fig. 13. Monthly SAT anomalies in Ukraine for 1990—2021: *1* — March; *2* — April; *3* — May; *1a*, *2a*, *3a* — the respective linear trends.

Berehove (–0.03 °C per decade), Uzhhorod (–0.04 °C per decade), and Velykyi Bereznyi (–0.05 °C per decade) (Fig. 12, May).

The evolution of monthly temperature anomalies in spring, as well as the occurrence of anomalously warm or cold months over 1990—2021, are shown in Fig. 13 and Table. The warmest years during spring months occurred in March (2014, 2017, 2020), April (2000, 2016, 2018), and May (2003, 2012, 2013, 2018). The coldest springs were observed in March (1996, 2005, 2018), April (1992, 1997, 2003), and May (1991, 1999, 2020).

Summer. In recent decades, heatwaves, anomalously high temperatures, and droughts have become increasingly frequent across Europe, including in Ukraine [Twardosz, Kossowska-Cezak, 2021; Twardosz et al., 2021]. The average monthly surface air temperatures across Ukraine for June, July, and August are 19.6 ± 1.3 °C, 21.8 ± 1.7 °C, and 21.1 ± 1.9 °C, respectively. Analysis of long-term trends over the period 1990—2021 reveals a clear warming trend across all summer months. The average warming trends in Ukraine are: +0.97 ± 0.16 °C per decade in June; +0.60 ± 0.13 °C per decade in July; +0.85 ± 0.19 °C per decade in August (Fig. 14). In June, particularly intense warming (up to +1.12 ± 0.13 °C per decade) is observed in the northern and central regions of Ukraine. Meanwhile, in August, the highest rates of warming occur in the eastern and southern regions. Among the summer months, July

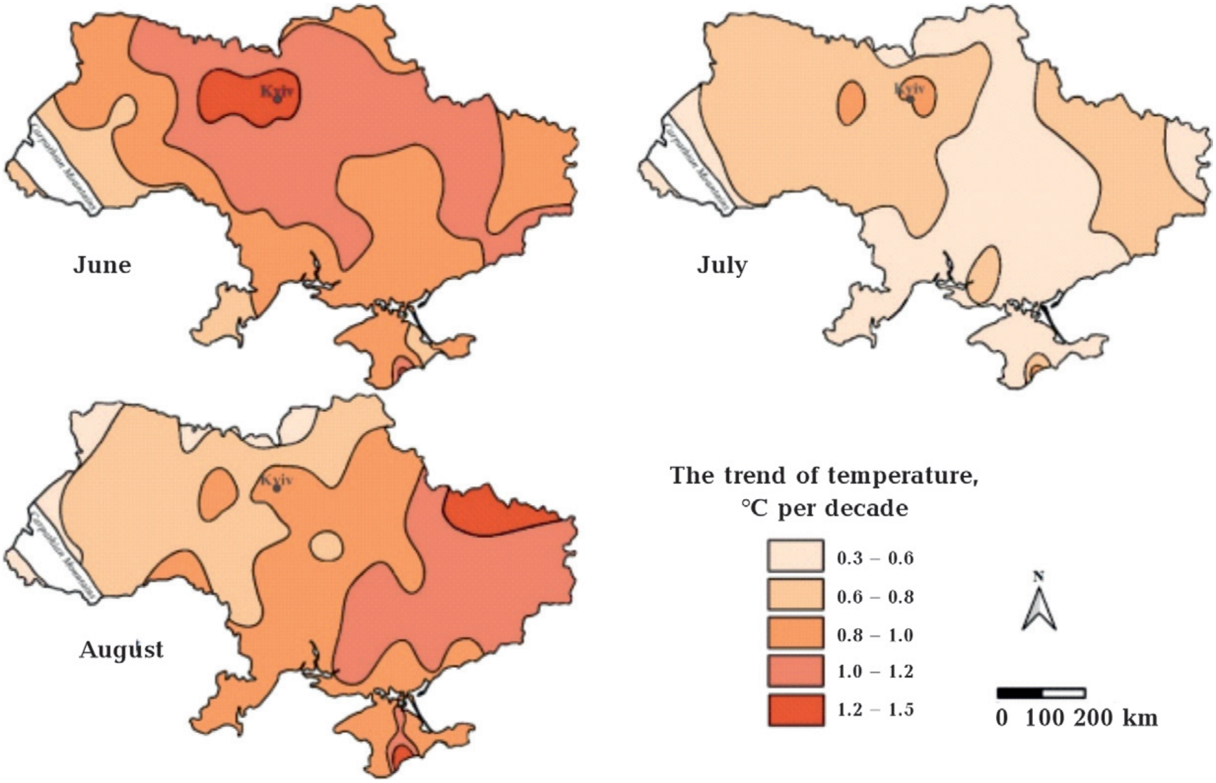

Fig. 14. Spatial distribution of monthly SAT trends in June, July, and August across Ukraine (1990—2021).

shows the lowest overall warming trend. However, Kyiv stands out for exhibiting one of the most rapid warming rates, likely attributed to urban heat island effects driven by intensive urbanization and localized microclimatic changes.

The evolution of monthly surface air temperature anomalies during summers in Ukraine for the period 1990—2021 is presented in Fig. 15 and Table. These anomalies suggest that warm summers predominated. The warmest years occurred in June (1999, 2010, 2019), July (2001, 2002, 2021), and August (2010, 2017, 2018). Conversely, the coldest years were observed in June (1993, 1994, 2001), July (1990, 1993, 1997), and August (1990, 1993, 1997).

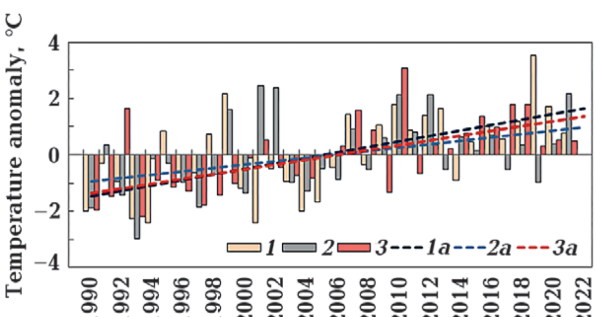

Fig. 15. Monthly SAT anomalies in Ukraine for 1990—2021: *1* — June; *2* — July; *3* — August; *1a*, *2a*, *3a* — the respective linear trends.

Autumn. In Ukraine, autumn is marked by a relatively rapid rise in temperatures, with September often exhibiting summer-like conditions. The average monthly surface air temperatures across the country for September, October, and November are 15.5 ± 1.8 °C, 9.4 ± 1.8 °C, and 3.7 ± 1.9 °C, respectively. Over the period 1990—2021, the spatial distribution of average monthly temperature trends during autumn shows predominantly positive values, indicating consistent warming, albeit with regional variations. The average warming trends are: +0.90 ± 0.13 °C per decade in September; +0.40 ± 0.12 °C per decade in October; +0.87 ± 0.17 °C per decade in November (Fig. 16). Notably, lower warming trends were observed in the southern regions, Crimea, and Zakarpattia, suggesting localized climate moderation effects.

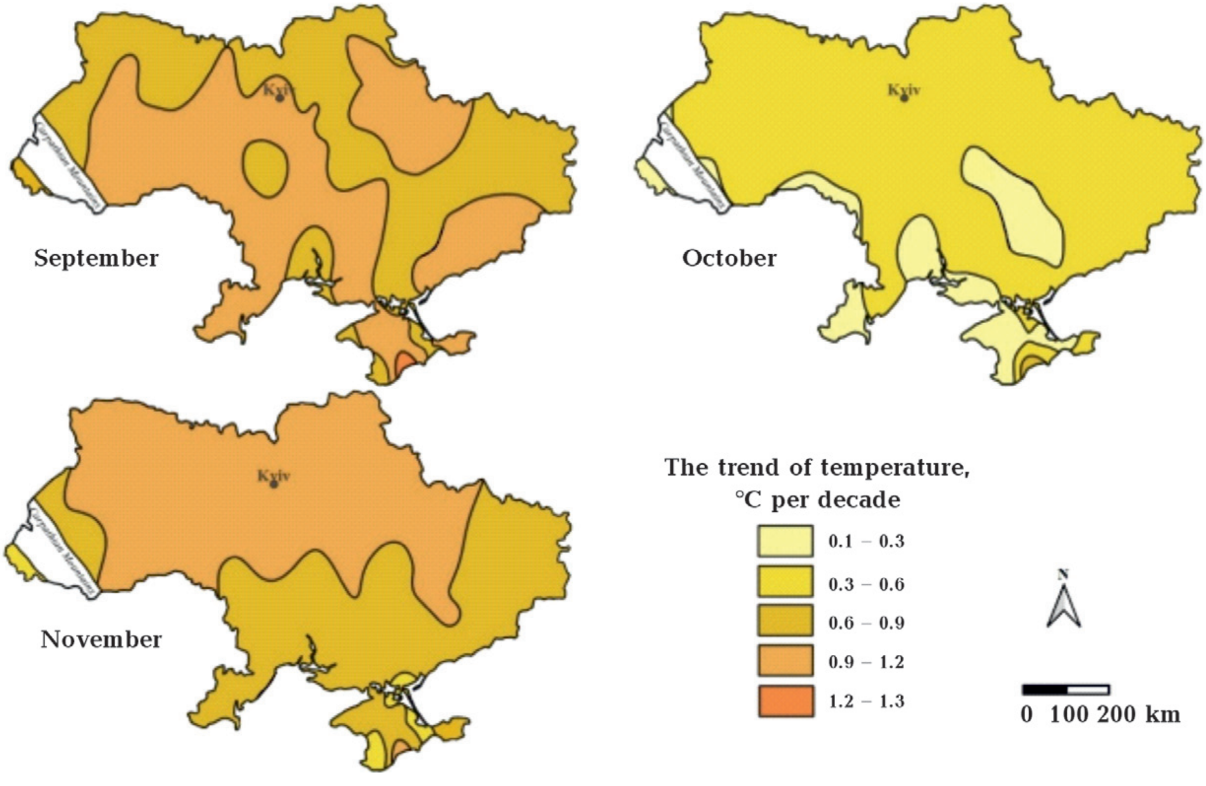

Fig. 16. Spatial distribution of monthly SAT trends in September, October, and November across Ukraine (1990—2021).

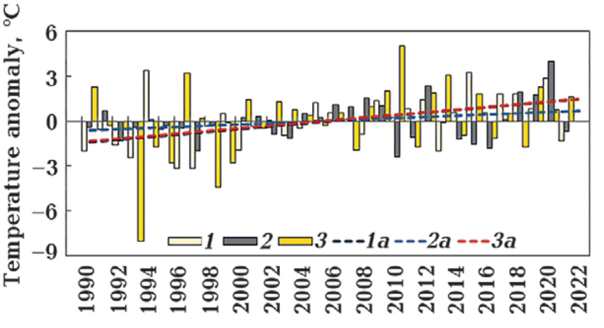

Fig. 17. Monthly SAT anomalies for September, October, and November in Ukraine (1990—2021): *1* — September; *2* — October; *3* — November; *1a*, *2a*, *3a* — the linear trends, respectively.

The monthly SAT anomalies during the autumns in Ukraine (1990—2021) are illustrated in Fig. 17 and Table. These anomalies demonstrate a clear warming signal over the last three decades. In particular, the frequent occurrence of positive SAT anomalies in recent years confirms that autumns have become significantly warmer in Ukraine. Pronounced warming was observed in September (1994, 2015, 2020), October (2012, 2018—2020), and November (1996, 2010, 2013). Cold anomalies were more common in September (1993, 1996, 1997), October (1997, 2015, 2016), and November (1993, 1995, 1998, 1999).

Importantly, a comparative analysis of monthly temperature trends reveals a progressive increase in warming from June to December. In contrast, the period from January to June is characterized by lower or even negative trend values (see Figs. 10, 12, 14, 16). A comprehensive summary of the highest and lowest annual and monthly surface air temperature anomalies for the period 1990—2021 is presented in Table. It highlights that the coldest years during this period were primarily observed in the 1990s (e.g., 1991—1993, 1996—1998) and early 2000s (2003, 2006). In contrast, the warmest years occurred predominantly in the last decade, particularly 2007, and 2015—2020.

Discussion. This study analyzed surface air temperature trends across Ukraine over recent decades, offering valuable insights

Summary of annual and monthly surface air temperature extremes in Ukraine (1990—2021) (blue is cold anomaly value, red is warm anomaly value)

Year	Month												$<T_{year}>$
	1	2	3	4	5	6	7	8	9	10	11	12	
1990		2.4	6.1			17.6	19.9	19.1	13.5				
1991		–5.0			13.1			19.6					
1992				7.7	13.6		20.4	22.7		8.0			
1993				8.0		17.3	18.8	18.9	13.1		–4.3		7.8
1994	0.9				13.9	17.2			18.9				
1995		2.3									0.9	–4.2	
1996	–7.5	–5.5	–1.9		18.1				12.3		6.9		8.1
1997	–5.5			6.1			19.9	19.3	12.3	7.4			8.0
1998								19.7			–0.7	–4.3	
1999					12.9	21.8	23.4				0.9		
2000				12.6					13.6			2.0	
2001						17.2	24.2					–5.9	
2002		3.5	5.5				24.2					–7.2	
2003		–6.5	0.0	7.1	18.8								
2004					13.7	17.6							
2005	0.2		–0.4			17.9							
2006	–7.4	–5.1										2.2	
2007	2.5		5.6		17.9			22.7					10.6
2008			5.3							11.0			
2009								19.8					
2010	–6.1					21.4	23.9	24.2		7.0	8.7		
2011		–5.0										2.5	
2012		–8.9		11.9	18.4		23.9			11.7			
2013			0.7		18.8	21.2			13.5		6.8		
2014			6.4										
2015								22.5	18.7	7.8		2.1	10.6
2016		3.1		12.0						7.6			
2017			6.2					22.9	17.3			3.4	
2018			–0.1	13.0	18.4			22.9	17.3	11.4			
2019						23.1				11.2		3.1	11.0
2020	0.9	2.3	6.5		13.3	21.3			18.4	13.4			11.2
2021				8.0			24.0						
$<T_m>$	–2.4	–1.5	3.0	9.8	15.6	19.6	21.8	21.1	15.5	9.4	3.7	–0.8	9.6
±σ	2.3	2.9	2.2	1.5	1.7	1.5	1.4	1.3	1.7	1.4	2.5	2.5	0.8

into the region's evolving climate dynamics. The results confirm a statistically significant warming trend, in line with global climate patterns, yet characterized by distinct regional and seasonal variations. Notably, the rate of warming in Ukraine exceeds the global average, as similarly reported in long-term analyses by Boychenko & Maidanovych [2024] based on century-long SAT datasets.

Temperature trends in Ukraine are shown to be strongly influenced by geographic location, seasonality, and the temporal resolution of observational data — a point supported by earlier studies [Krauskopf, Huth, 2020]. For instance, Pokorná et al. [2018] demonstrated that the strongest warming periods in Eastern Europe occurred in mid-January, early March, and mid-May to early August, depending on the region and season.

Our findings align with regional trends across Eastern Europe [Anders et al., 2014; Rousi et al., 2022], but reveal locally specific warming signatures. The most pronounced increases in SAT were observed in winter and spring, suggesting potential shifts in atmospheric circulation, snow cover dynamics, or solar radiation balance. In contrast, summer warming was more moderate and spatially variable, possibly due to soil moisture feedback, evapotranspiration rates, or urban heat island effects, especially in metropolitan areas such as Kyiv.

A comparative analysis by Pyasetska & Shcheglov [2023] further supports these trends, revealing a general increase in monthly SAT for 2006—2020 compared to 1991—2005. Interestingly, they observed localized January cooling, which may represent a novel feature of the evolving Ukrainian climate and aligns with anomalies identified in the present study.

Further insight is provided by Osadchyi et al. [2018], who analyzed SAT extremes in Ukraine between 1946 and 2015. They reported significant increases in both maximum and minimum temperatures, especially from 1981 onward. The most rapid increases occurred during the summer, with trends of +0.94 °C per decade for maximum temperatures and +0.61 °C per decade for minimum temperatures. Additionally, maximum temperatures tended to increase faster than minimum temperatures in all seasons except winter.

These seasonal discrepancies in SAT trends may signal a gradual shift in Ukraine's continental climate characteristics [Boychenko et al., 2017, 2018]. As summer temperatures rise more rapidly than winter temperatures, the traditional seasonal contrast may weaken, potentially driving the region toward a more temperate or even subtropical climatic profile. Such transformations would have profound implications for ecosystems, agriculture, and hydrological cycles.

A broader European context is provided by Twardosz et al. [2021], who found that between 1985 and 2020, the strongest warming occurred in spring (+0.061 °C/year), followed by summer and winter, while autumn warming was least pronounced (+0.045 °C/year). Ukraine's warming patterns are broadly consistent with these findings, though regional variability within Ukraine remains more complex, especially in winter and summer. The northeastward intensification of warming, especially in winter and spring, and southward patterns in summer, further illustrate Ukraine's transitional climatic positioning within Europe.

Understanding these spatiotemporal SAT trends is critical for climate risk assessment and policy development, particularly in the areas of agriculture, infrastructure resilience, and water resource management. To improve adaptation strategies, future research should prioritize high-resolution climate modeling, incorporating additional variables such as precipitation, humidity, and extreme weather events, to enhance projections of localized climate impacts.

Conclusion. The analysis of surface air temperature dynamics in Ukraine over the period 1990—2021 reveals a distinct and consistent warming trend, with notable seasonal and regional variability. According to meteorological observations (weather dataset Ω_{93}), the average annual SAT in Ukraine for this period was 9.6 ± 0.8 °C. Over the past three decades, the mean rate of temperature increase reached approximately +0.64 ± 0.01 °C per decade, significantly exceeding historical norms. The pattern of annual temperature anomalies further supports this conclusion: only three years — 1993, 1996, and 1997 — exhibited negative anomalies (from –0.32 to –0.55 °C), while all other years were anomalously warm, with particularly high anomalies recorded in 2007, 2015, 2019, and 2020 (up to +2.79 °C).

Analysis of monthly SAT trends during the study period revealed statistically significant warming in nearly all months, ranging from +0.34 °C to +1.19 °C per decade. The strongest warming was observed in December

(+1.19 ± 0.14 °C per decade), particularly in northern and eastern regions of Ukraine. In contrast, January exhibited minimal or even negative trends in many areas, except for Crimea and southern Ukraine, where moderate warming persisted.

The amplitude and phase of the first harmonic of seasonal SAT variations serve as reliable indicators of continental climatic effects. Based on Fourier analysis, the mean amplitude of the seasonal SAT cycle for 1990—2021 was 12.3 ± 1.0 °C, with a decreasing trend of approximately 0.1 °C per decade, primarily driven by summer season warming. The mean phase of the seasonal cycle was estimated at 1.29 ± 0.06 months. A slight phase shift of –0.012 months per decade was also detected over the study period.

Overall, these results provide robust evidence of regional climate change in Ukraine, underscoring the urgent need to adapt national strategies. Future research should prioritize high-resolution climate modeling to better forecast local impacts, particularly in climate-vulnerable areas. Integrating the analysis of extreme weather events, such as heatwaves, droughts, and intense precipitation, is also crucial, as their frequency and intensity are projected to increase. Practically, these findings are vital for developing targeted policies in the agricultural sector, including adjusting planting schedules and crop selection, for urban planning to mitigate the urban heat island effect, and for managing water resources and ecosystems to ensure their resilience in a warming climate.

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Дослідження сезонних тенденцій зміни приземної температури повітря в Україні (1990—2021)

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У дослідженні вивчалися просторово-часові характеристики змін температури приземного повітря в Україні за період 1990—2021 рр., зосереджуючись на сезонній та регіональній мінливості, довгострокових трендах і гармонічних характеристиках річного циклу температури, а також їхніх наслідках для регіональних змін клімату.

Середня річна температури приземного повітря за аналізований період (використовувався набір метеорологічних спостережень Ω93) становила 9.6±0.8 °C, що помітно на 1,2 °C вище кліматичної норми 1961—1990 рр. (8,4±1,1 °C). Протягом цих трьох десятиліть середня швидкість зростання температури досягла значних позначок (0,64±0,01 °C) за десятиліття, суттєво перевищуючи історичні середні показники. Ця тенденція потепління підтверджується річними температурними аномаліями: лише три роки (1993, 1996, 1997) демонстрували негативні аномалії (від –0,32 до –0,55 °C), тоді як інші роки були аномально теплими, з піками у 2007, 2015, 2019 та 2020 р. (до +2,79 °C).

Аналіз місячних трендів температури приземного повітря виявив статистично значуще потепління майже в усі місяці, у діапазоні від +0,34 °C до +1,19 °C за десятиліття. Найінтенсивніше потепління спостерігалося у грудні (+1,19±0,14 °C за десятиліття), особливо в північних і східних регіонах України. Натомість, січень демонстрував мінімальні або навіть негативні тренди у багатьох регіонах, за винятком Криму та півдня України, де помірне потепління зберігалося.

Амплітуда та фаза сезонних коливань приземної температури повітря є надійними індикаторами континентальних кліматичних характеристик. У період 1990—2021 рр. середня амплітуда сезонного температурного циклу становила 12,3 ± 1,0 °C зі знижувальною тенденцією приблизно на 0,1 °C за десятиліття. Це зниження переважно зумовлене потеплінням у теплий період року. Середнє значення фази сезонного циклу оцінено як 1,29 ± 0,06 місяця. Упродовж досліджуваного періоду спостерігалося незначне зміщення фази на –0,12 місяця за десятиліття.

Дослідження підкреслює підвищену мінливість температури протягом зимових і весняних місяців, що сприяє більш повному розумінню сучасних кліматичних змін в Україні. Ці висновки підкреслюють нагальну потребу в адаптивних стратегіях для пом'якшення наслідків поточних кліматичних змін.

Ключові слова: зміна клімату, приземна температура повітря, температурні аномалії, амплітуда та фаза сезонного коливання температури.