CHAPTER 19

LONG-TERM TEMPERATURE CHANGE IN UKRAINE (1900–2021): TRENDS, VARIABILITY AND SCENARIOS

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DOI https://doi.org/10.30525/978-9934-26-654-6-19

INTRODUCTION

Human influence on the climate system is now firmly established, with greenhouse-gas emissions from energy production, land-use changes, and consumption patterns driving a sustained rise in global mean temperature[1, 2]. Recent assessments indicate that global surface temperature has already exceeded the pre-industrial baseline by more than 1 °C, and the last decade has been marked by an exceptional sequence of record-warm years[3]. The global signal manifests regionally through shifts in the frequency of temperature extremes, changes in seasonal regimes, and altered spatial gradients of warming climate[4, 5].

Ukraine provides a valuable setting for examining these processes because it lies at the intersection of Atlantic-European influences and continental air-mass regimes. The country exhibits pronounced spatial heterogeneity in temperature variability shaped by geography and atmospheric circulation[6]. Observations indicate an overall warming background, accompanied by

[1] IPCC, 2023: Summary for Policymakers. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / Core Writing Team, H. Lee and J. Romero (eds.). Geneva : IPCC, 2023. P. 1–34. DOI: 10.59327/IPCC/AR6–9789291691647.001.

[2] Climate Change 2021 – The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2023. P. 553–672. DOI: 10.1017/9781009157896.006.

[3] WMO. Provisional State of the Global Climate. 2022. URL: https://reliefweb.int/report/world/wmo–provisional–state–global–climate–2022 (accessed on 15 January 2026).

[4] Hegerl G. C., Brönnimann S., Schurer A., Cowan T. The early 20th–century warming: Anomalies, causes, and consequences. *Wiley Interdisciplinary Reviews: Climate Change*. 2018. Vol. 9, № 4. e522. DOI: 10.1002/wcc.522.

[5] Nita I. A., Sfîcă L., Voiculescu M., Birsan M. V., Micheu M. M. Changes in the global mean air temperature over land since 1980. *Atmospheric Research*. 2022. Vol. 279. 106392. DOI: 10.1016/j.atmosres.2022.106392.

[6] Клімат України / за ред. В. М. Ліпінського, В. А. Дячука, В. М. Бабіченко. Київ : Вид-во Раєвського, 2003. 344 с.

a decreasing likelihood of extremely cold conditions and an increasing occurrence of anomalously warm episodes[7, 8]. At the same time, substantial interannual variability persists, making it essential to distinguish long-term changes from circulation-driven fluctuations.

While global and regional modelling ensembles provide indispensable context for future projections[9, 10], long observational records remain fundamental for diagnosing regional climate change. Extended series establish a historical baseline, allow detection of changes in the seasonal cycle and extremes, and support the evaluation of modelling approaches. For Ukraine, early instrumental measurements available for some locations add further value by extending the perspective beyond the twentieth century.

Against this background, the present work examines the spatiotemporal behavior of surface air temperature over Ukraine with a focus on long-term change and the transformation of the seasonal cycle. In addition, we assess a semi-empirical modelling approach for estimating average annual surface air temperature over the lowland (plain) part of Ukraine by comparing modelled estimates with observed values. This emphasis reflects the need for transparent, computationally efficient tools that can complement more resource–intensive numerical modelling frameworks in climate impact studies and applied environmental planning.

Materials and Methods. This study relies on an analysis of long-term changes in mean annual near-surface air temperature of Ukraine. For Ukraine, monthly mean air temperature series were assembled from 45 meteorological stations (dataset $\Omega_{1900–2021}$) and used to derive average monthly values for 1900–2021 by spatial averaging across the network[11, 12]. Stations were selected to ensure (i) observations commencing around 1900,

[7] Волощук В. М., Бойченко С. Г. Сценарії можливих змін клімату України в XXI столітті (під впливом глобального антропогенного потепління). *Клімат України* / за ред. В. М. Ліпінського, В. А. Дячука, В. М. Бабіченко. Київ : Вид-во Раєвського, 2003. С. 308-331.

[8] Wilson L., New S., Daron J., Golding N. Climate Change Impacts for Ukraine. *Met Office*. 2021. URL: https://mepr.gov.ua/wp–content/uploads/2023/07/2_Vplyv–zminy–klimatu–v–Ukrayini.pdf (accessed on 15 January 2026).

[9] IPCC, 2023: Summary for Policymakers. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / Core Writing Team, H. Lee and J. Romero (eds.). Geneva : IPCC, 2023. P. 1–34. DOI: 10.59327/IPCC/AR6–9789291691647.001.

[10] Jacob D., Teichmann C., Sobolowski S., Katragkou E., Anders I., Belda M. et al. Regional climate downscaling over Europe: perspectives from the EURO–CORDEX community. *Regional Environmental Change*. 2020. V. 20, № 2. P. 51. DOI: 10.1007/s10113–020–01606–9.

[11] CGO. *Central Geophysical Observatory* of empirical data, 2021. URL: http://cgo–sreznevskyi.kyiv.ua/index.php?lang=en&fn=u_klimat&f=ukraine&p=1 (accessed on 29 November 2023).

[12] Climate Explorer. URL: http://climexp.knmi.nl/selectstation.cgi?id=someone@somewhere (accessed on 15 January 2026).

(ii) a proportion of missing data not exceeding 25 %, and (iii) a broadly even spatial distribution, while limiting elevation effects by restricting station altitudes to approximately ≤350–400 m.

Data gaps occur in several intervals and reflect well-known historical disruptions, with the largest discontinuities associated with the First World War and the subsequent period of political instability in the former Russian Empire (approximately 1914–1925), as well as the Second World War (1939–1945). In addition, station records for parts of eastern and southern Ukraine are incomplete for 2014–2023 due to the ongoing Russian aggression and resulting constraints on data availability.

The location of meteorological stations, which were used for analyses, is shown in Figure 1.

Fig. 1. Location of meteorological stations (used in this study) on the territory of Ukraine

Furthermore, using empirical observations from the Ukrainian network of meteorological stations for 1900–2021 and 1991-2021, we examined the spatiotemporal patterns of annual and seasonal surface air temperature. The seasonal temperature cycle was approximated by a first-order Fourier representation (a single annual harmonic), which enables an objective estimation of the amplitude and phase of the annual temperature wave[13]:

[13] Von Storch H., Zwiers F. W. Statistical analysis in climate research. Cambridge University Press, 1999. 495 p.

$$T_m^k \approx T_o^k + a sin\frac{2\pi(m-0.5)}{12} + b cos\frac{2\pi(m-0.5)}{12},$$

$$a = \frac{1}{6}\sum T_m sin\frac{2\pi(m-0.5)}{12}, b = \frac{1}{6}\sum T_m cos\frac{2\pi(m-0.5)}{12}, \quad (1)$$

$$T_o^k = \frac{1}{12}\sum_m T_m^k, m = 1,2,\dots,12, \quad A = \sqrt{a^2+b^2}, F = arctg\frac{b}{a},$$

here, *k* denotes the meteorological station, *m* is the month index, T_m^k is the mean monthly temperature, T_o^k is the mean annual temperature, *A* is the amplitude (°C), and *F* is the phase expressed in months.

The 1900–2021 period was used to characterize long-term trends in annual and monthly temperature and to provide a baseline for comparison with changes observed in the recent climate period. Climatic normal for 1991–2020 were calculated from station data, whereas the 1961-1990 normal were taken from the Climate Cadastre of Ukraine[14]. To quantify changes in the seasonal temperature course, linear trend coefficients were computed for each month at each station and subsequently averaged over the study area to obtain territory-wide estimates.

Three Shared Socioeconomic Pathways (SSP) projections of Ukraine's annual mean near-surface air temperature: SSP1-2.6, SSP2-4.5, and SSP3-7.0 were derived from the Berkeley Earth dataset. These scenarios represent projected temperature change relative to a late-19th-century (pre-industrial) baseline and correspond to alternative greenhouse-gas emissions trajectories through 2100[15].

The Berkeley Earth team has developed a statistical methodology to derive large-scale temperature anomalies from weather-station observations. A key advantage of this approach is that it can accommodate short, fragmented, and temporally discontinuous station records, allowing a substantially larger fraction of available measurements to be retained in the analysis. The method applies network-based weighting that accounts for station consistency and data quality within the surrounding spatial context, so that records with different uncertainty levels contribute appropriately without disproportionately influencing the reconstructed signal.

Trends were estimated using linear least-squares regression. The statistical significance of monotonic trends was evaluated with the non-parametric

[14] Кліматичний кадастр України. Стандартні норми за період 1961–1990 рр. Київ : Центральна геофізична обсерваторія, 2005. 48 с.

[15] Berkeley Earth. URL: http://berkeleyearth.org (accessed on 15 January 2026).

Mann-Kendall test at the 95 % confidence level. Data processing followed standard statistical procedures commonly applied to meteorological time series. Descriptive statistics, significance testing, and plotting were performed in MS Excel and XLSTAT.

Spatial mapping was carried out in QGIS and SAGA GIS. To generate continuous surfaces of the meteoparameters from the station network, we applied radial basis function interpolation using the thin-plate spline kernel, a method widely used for climatological interpolation, particularly when input points are relatively sparse[16, 17].

1. Long-time changes of average annual surface air temperature on the territory of Ukraine for the period from 1900 to 2021

Since 1880, the annual global surface air temperature has fluctuated, showing an overall signification upward tendency[18]. The annual surface air temperature anomaly was at its highest point in 2020, at 1.65 degrees above average. Anomalies in surface temperature in Ukraine followed a similar trend over the same period[19].

The long-term average annual surface air temperatures on the territory of Ukraine for the period from 1900 to 2021 are shown in Figure 2. According to the analysis of meteorological data, the average annual surface air temperature on the territory of Ukraine for the period 1900–2021 was 8.6 ± 0.9 °C. However, for the more recent period of 1991–2020, it increased to 9.5 ± 0.9 °C. Notably, the climatic norm of temperature for the period 1961–1990 was 8.4 ± 0.9 °C. The temperature in Ukraine exhibited an increase of 1.31 ± 0.42 °C per 100 years during the period 1900–2021. It's worth noting that climate change has accelerated significantly since the second half of the 20th century. Over the last 30 years (for the last climatic norm 1991–2020), a more pronounced increase in annual surface temperature, by 0.79 ± 0.08 °C per decade, was observed, contrasting with the trend of

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[16] Boer E. P., de Beurs K. M., Hartkamp A. D. Kriging and thin plate splines for mapping climate variables. *International Journal of Applied Earth Observation and Geoinformation*. 2001. Vol. 3, № 2. P. 146–154. DOI: 10.1016/S0303–2434(01)85006–6.

[17] Smith T. B., Smith N., Weleber R. G. Comparison of nonparametric methods for static visual field interpolation. *Medical & biological engineering & computing*. 2017. Vol. 55. P. 117–126. DOI: 10.1007/s11517–016–1485–x.

[18] IPCC, 2023: Summary for Policymakers. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / Core Writing Team, H. Lee and J. Romero (eds.). Geneva: IPCC, 2023. P. 1–34. DOI: 10.59327/IPCC/AR6–9789291691647.001.

[19] Boychenko S., Maidanovych N. A century-long tendency of change in surface air temperature on the territory of Ukraine. *Geofizychnyi Zhurnal*. 2024. Vol. 46, № 2. P. 53–79. DOI: 10.24028/gj.v46i2.297227.

the climatic norm for the period 1961–1990, which showed a decrease of −0.02 ± 0.15 °C per decade.

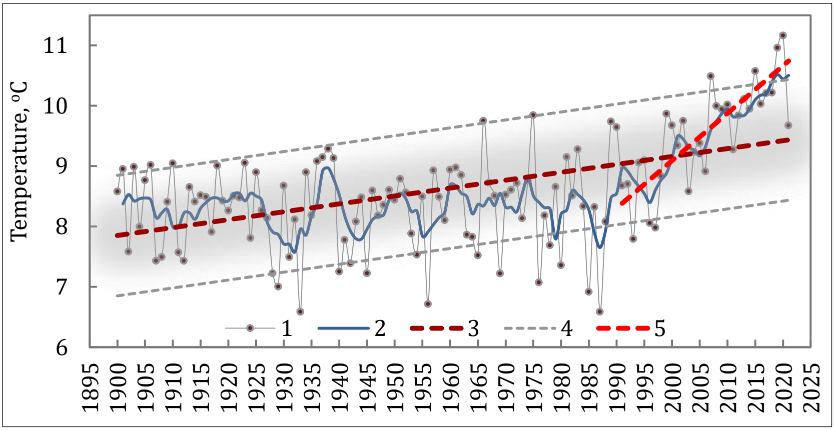
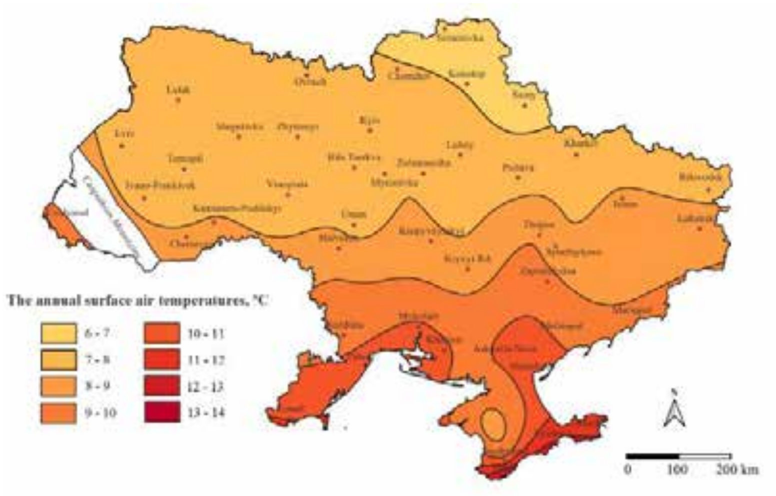


Fig. 2. Long-term average annual surface air temperatures
1 is averaged time series for 45 weather stations; 2 is five-year moving averages 4 is the standard deviation (±σ); 3 and 5 are linear trends for the periods 1900–2021 and 1991–2020) on the territory of Ukraine

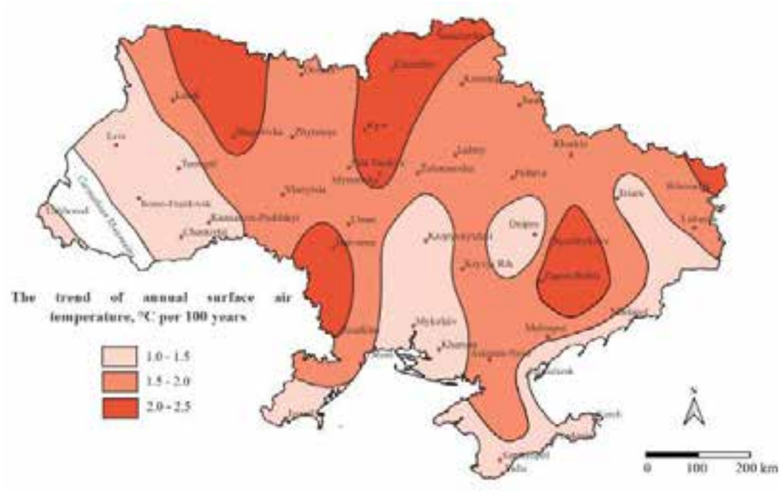
The spatial distribution of averaged annual surface air temperature and corresponding trends on the territory of Ukraine from 1900 to 2021 are shown in Figure 3. Changes in the temperature regime exhibit spatial-temporal peculiarities within Ukraine. A temperature increases within the range of 1.5–2.0 °C has been observed in most parts of the country from 1900 to 2021. Simultaneously, some parts of northern, northwestern, and eastern regions, as well as Vinnytsia and Zaporizhzhia oblasts, are characterized by more intense warming, reaching 2.0–2.5 °C, in contrast to southwestern, southern regions, and the territories adjacent to the Ukrainian Carpathians, where the temperature rise is within 1.0–1.5 °C. This is likely associated with both the latitude distribution peculiarities of global warming and the continental nature of climate conditions, along with regional features of atmospheric circulation[20, 21].

[20] Волощук В. М., Бойченко С. Г. Сценарії можливих змін клімату України в XXI столітті (під впливом глобального антропогенного потепління). *Клімат України* / за ред. В. М. Ліпінського, В. А. Дячука, В. М. Бабіченко. Київ: Вид-во Раєвського, 2003. С. 308–331.

[21] Бойченко С. Г. Напівемпіричні моделі та сценарії глобальних і регіональних змін клімату / за ред. В. М. Волощука. Київ : Наукова думка, 2008. 310 с. URL: https://www.researchgate.net/publication/321301027.



(a)



(b)

Fig. 3. The spatial distribution of averaged annual surface air temperature (a) and corresponding trends (b) on the territory of Ukraine from 1900 to 2021

The anomaly for a specific variable and year is calculated as the difference between the variable's value for that year and the multiannual average value of the variable or climatic norm. It should be noted that the approach to the estimated anomalies from multi-annual averages of global mean temperature can be used for monthly averages[22, 23]. The average annual surface air temperature anomalies (ΔT) were calculated from the annual average value (weather data set $\Omega_{1900-2021}$) relative to the 1880–1900 pre-industrial average $\left(\Delta T = T_{year} - \left\langle T_{\langle 1880-1900\rangle}\right\rangle\right)$[24]. Temperature anomalies from 1900 to 2021 indicate the coldest annual averages occurred in 1933, 1956, 1976, 1985, and 1987 ($\Delta T = -0.68 \pm 0.54$ °C), while the hottest annual averages were observed in 2007, 2015, 2019, and 2020 ($\Delta T = 0.74 \pm 0.63$ °C) (see Figure 4). In the recent decade, there has been a significant increase in temperature in Ukraine, as well as globally.

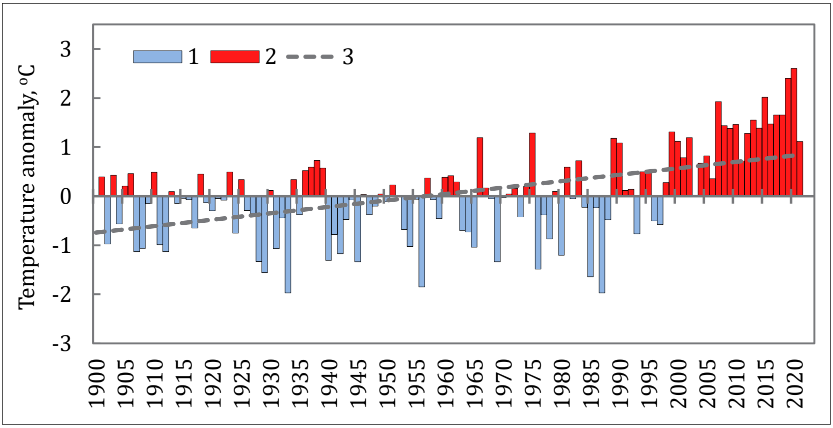


Fig. 4. The average annual surface air temperature anomalies
1 is the coldest annual average, 2 is the hottest annual average, and 3 is the linear trend on the territory of Ukraine for the period from 1900 to 2021

An analysis of interannual temperature variability *var{T}* (root-mean-square error) relative to long-term annual means *avr*{*T*} across Ukraine (1900–2021) reveals a clear spatial gradient. The highest *var*{*T*} values are concentrated in the cooler northwestern, northern, and northeastern regions.

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[22] Climate Bulletin – about the data and analysis. URL: https://climate.copernicus.eu/climate–bulletin–about–data–and–analysis (accessed on 15 January 2026).

[23] State of the Global Climate. 2021. URL: https://library.wmo.int/viewer/56294?medianame =State_of_the_Global_Climate_2021_#page=1&viewer=picture&o=download&n=0&q= (accessed on 15 January 2026).

[24] Boychenko S., Maidanovych N. A century-long tendency of change in surface air temperature on the territory of Ukraine. *Geofizychnyi Zhurnal*. 2024. Vol. 46, № 2. P. 53–79. DOI: 10.24028/gj.v46i2.297227.

Conversely, the lowest variability is observed in the warmer southern, southwestern, and southeastern areas. This latitudinal intensification of warming rates towards the north aligns with broader climate trends observed across the Northern Hemisphere[25].

Known that the climatic conditions of Ukraine are shaped by the interplay of various external and internal factors[26]. Global influences encompass the planet's spatial orientation and the influx of solar electromagnetic radiation. Zonal factors involve the latitudinal characteristics of heat exchange distribution in temperate latitudes, the westward movement of air masses from the Atlantic, and meridional flows of air masses. Regionally, the orographic features of the terrain, proximity to seas, and local atmospheric circulation play pivotal roles. Local factors, including regional winds, the impact of water bodies, vegetation, and other elements, contribute to the formation of microclimatic characteristics in specific areas.

2. The annual cycle of surface air temperature on the territory of Ukraine

The seasonal course of the surface air temperature in Ukraine has characteristic features of temperate latitudes. On average, the maximum temperature in Ukraine is observed in summer (from 18.9 to 20.9 °C), the minimum – in winter (from −1.6 to −4.1 °C). In transitional seasons the average temperatures are from 1.3 to 15.2°C (in spring) and from 15.1 to 3.1 °C (in autumn). The annual cycle of averaged time series of surface air temperature for the $\Omega_{1900–2021}$ weather data set and their approximation on the territory of Ukraine in the period of 1900–2021 are shown in Figure 5. The comparison of the model monthly temperatures with their factual values presented that the reliability of the linear regression (R^2) is 0.97–0.99.

The seasonal pattern of temperature root-mean-square errors used here as an indicator of weather variability shows a clear cold-season maximum and warm-season minimum across Ukraine. The highest root-mean-square error occurs in January-February (3.2–3.5 °C), while the lowest values are observed during summer, reaching ~1.6–1.7 °C. The monthly course of root-mean-square errors 1900–2021 indicating that interannual temperature variability is substantially larger in winter than in summer. Against the backdrop of

[25] Волощук В. М., Бойченко С. Г. Сценарії можливих змін клімату України в XXI столітті (під впливом глобального антропогенного потепління). Клімат України / за ред. В. М. Ліпінського, В. А. Дячука, В. М. Бабіченко. Київ : Вид-во Раєвського, 2003. С. 308–331.

[26] Клімат України / за ред. В. М. Ліпінського, В. А. Дячука, В. М. Бабіченко. Київ : Вид-во Раєвського, 2003. 344 с.

ongoing climate change, many studies have reported seasonally differentiated temperature changes and shifts in seasonal temperature behavior[27, 28].

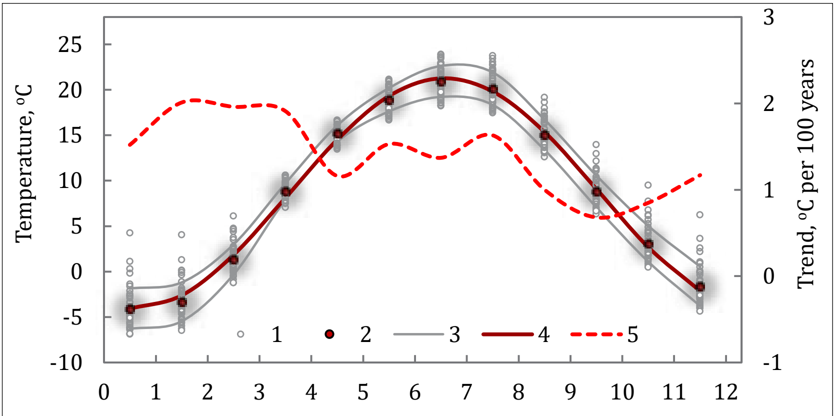

Fig. 5. The annual cycle of surface air temperature

1 is monthly data, 2 is average values for $\Omega_{1900–2021}$ dataset, 3 is ±σ,
4 is Fourier approximation and corresponding trends (5) on the territory of Ukraine for the period 1900–2021

For Ukraine over 1900–2021, the strongest warming is detected in the colder half of the year (October–March), with typical rates of ~0.7–2.0 °C per century, while the warm period (April–September) also warms, at ~1.0–1.9 °C per century. This seasonally structured signal is important because it implies not only a shift in mean temperature but also potential changes in thermal risks, phenological timing, and energy-demand seasonality.

The spatial distribution of average monthly surface temperature (in January, April, July, and October) on the territory of Ukraine has zonal differences, which are shown in Figure 6.

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[27] Boychenko S., Voloshchuk V., Kuchma T., Serdyuchenko N. Long-time changes of the thermal continentality index, the amplitudes, and the phase of the seasonal temperature variation in Ukraine. *Geofizicheskiy Zhurnal*. 2018. Vol. 40, № 3. P. 81–96. DOI: 10.24028/gzh.0203–3100.v40i3.2018.137175

[28] Twardosz R., Kossowska-Cezak U. Large-area thermal anomalies in Europe (1951-2018). Temporal and Spatial Patterns. *Atmospheric Research*. 2021. Vol. 251. 105434. DOI: 10.1016/j.atmosres.2020.105434.

Fig. 6. The spatial averaged monthly surface air temperature on the territory of Ukraine (January, April, July, and October) for the period 1900–2021

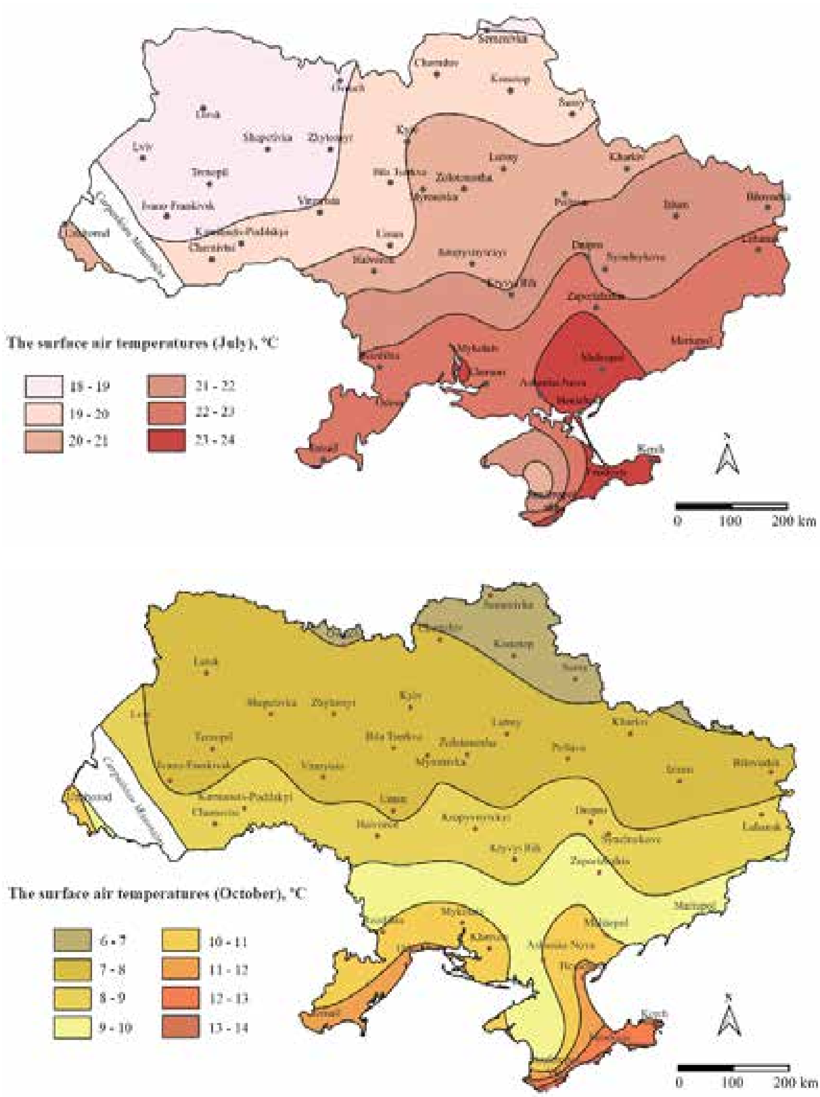

Fig. 6, page 422

The amplitude of surface air temperature is a useful integral indicator of climatic seasonality. For the station network beginning in 1900, the seasonal temperature amplitude (A) was calculated using Eq. (1). For Ukraine as a whole, the mean amplitude equals $A = 12.7 \pm 1.1$ °C for 1900–2021 and $A = 12.5 \pm 0.8$ °C for 1991–2020. Analysis of A over the 20th century and early 21st century indicates an overall decreasing tendency of about −0.5 to −0.1 °C per 100 years, driven primarily by stronger warming during the cold season. By contrast, for 1991–2020 the tendency is much weaker (−0.001 to −0.01 °C per decade) and is explained by the more substantial warming in the warm season, which partly offsets the earlier "cold-season-dominated" reduction in amplitude.

Previous studies have shown that, across Ukraine during the twentieth century, the rise in mean annual air temperature was accompanied by a reduction in the amplitude of the annual (seasonal) temperature cycle by about −0.4 °C per 100 years[29]. This pattern reflects stronger warming in the cold season and comparatively weaker warming in the warm season, resulting in a partial weakening of temperature "continentality".

Analysis of linear trends of the surface air temperature for several 30-year periods (meteorological norms) on the territory of Ukraine indicates certain differences (see Figure 7).

Substantial inter period variability is evident: both the sign and magnitude of trends for the same calendar month change markedly depending on the selected 30-year window. This indicates that the seasonal "warming profile" is not stable and is strongly contingent on the chosen baseline period, namely:

- 1951–1980 shows negative trends in a number of months, notably January (−0.6°C per decade) and December (down to −1.0 °C per decade), as well as negative values in the summer-autumn part of the year (June-October). This suggests that, during this 30-year interval, the "warming signal" had not yet become dominant across all seasons.
- 1961–1991 indicates warming in winter, especially toward the end and beginning of the year (January-March show positive trends), but distinct negative trends appear in late autumn, particularly November (pronounced cooling).
- 1971–2000 is characterized by mostly moderate positive trends during the cold half of the year and in part of the warm season; however, negative values persist for some months, especially November and December.

[29] Волощук В. М., Бойченко С. Г. Сценарії можливих змін клімату України в XXI столітті (під впливом глобального антропогенного потепління). *Клімат України* / за ред. В. М. Ліпінського, В. А. Дячука, В. М. Бабіченко. Київ : Вид-во Раєвського, 2003. С. 308–331.

• 1981–2010 shows positive trends in nearly all months, with maximum occurring in summer and late autumn (particularly July-August and November, where trends reach about 0.8–1.2 °C per decade).

• 1991–2020 exhibits the largest trend values: trends are positive almost throughout the year, with a clear intensification during the warm season and toward the end of the year. The strongest increases occur in September (0.9 °C per decade) and especially December (1.2 1.3 °C per decade). January is close to zero or slightly negative, highlighting pronounced within-season heterogeneity of the changes.

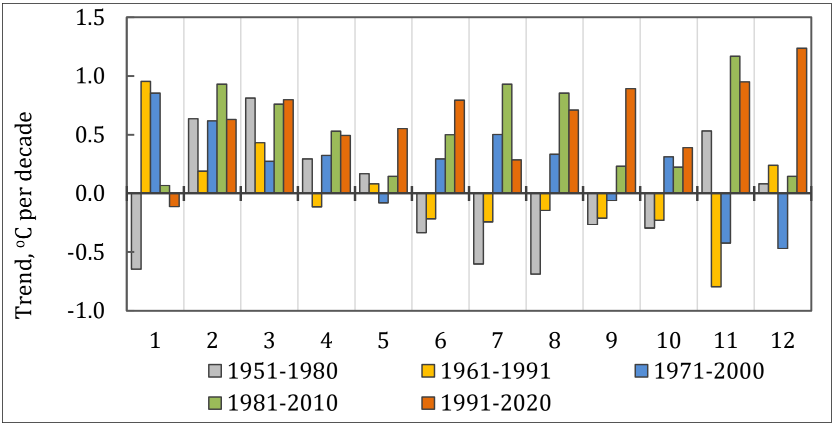

Fig. 7. Annual differences in linear trends of the surface air temperature for several 30-year periods on the territory of Ukraine

3. Scenarios of warming in Ukraine

Climate change scenarios are used to explore how different pathways of greenhouse-gas emissions and socio-economic development translate into future climate outcomes, thereby supporting mitigation and adaptation planning[30]. A robust feature across projections is that land areas tend to warm faster than oceans, largely due to lower effective heat capacity and differences in surface feedback; consequently, national land-based averages may exhibit a stronger warming signal than the global mean under the same

[30] IPCC, 2023: Summary for Policymakers. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / Core Writing Team, H. Lee and J. Romero (eds.). Geneva : IPCC, 2023. P. 1–34. DOI: 10.59327/IPCC/AR6–9789291691647.001.

scenario. At the same time, projections remain uncertain because climate models represent a complex, coupled system and differ in their sensitivity and regional responses to a given forcing trajectory[31].

In the IPCC Fifth Assessment Report (AR5), future forcing pathways were commonly represented by Representative Concentration Pathways (RCPs) – RCP2.6, RCP4.5, RCP6.0, and RCP8.5 – spanning low to very high radiative forcing by 2100[32]. In the CMIP6 framework, these pathways were updated and paired with Shared Socioeconomic Pathways (SSPs), which combine emissions trajectories with internally consistent assumptions about population, technology, energy systems, and policy choices[33]. The commonly used SSP-forcing combinations – SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 are designed to reach radiative forcing levels broadly comparable to the earlier RCP set by the end of the century, while offering a clearer socio-economic narrative context for each pathway[34].

Conceptually, SSP1 ("Sustainability") describes a world that increasingly prioritizes resource efficiency, low-carbon development, and inclusive growth-conditions that reduce challenges for both mitigation and adaptation. SSP2 ("Middle of the Road") reflects a continuation of historical development patterns with moderate improvements in efficiency but persistent structural constraints, producing intermediate challenges. SSP3 ("Regional Rivalry") emphasizes fragmented governance, weaker international cooperation, and higher barriers to mitigation and adaptation, which tends to sustain higher emissions and vulnerability. This framing is useful for Ukraine because it links the magnitude of projected warming not only to physical forcing, but also to the socio-economic context that shapes emissions and resilience.

For national-scale projections, a common approach is to derive a country-mean temperature series from climate-model output and then align (bias-adjust) the modelled baseline with observed historical data to ensure

[31] Climate Change 2021 – The Physical Science Basis. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2023. P. 553–672. DOI: 10.1017/9781009157896.006.

[32] Lee J., Marotzke J. et al. Future Global Climate: Scenario-Based Projections and Near-Term Information. Climate Change 2021: The Physical Science Basis / V. Masson-Delmotte et al. (eds.). Cambridge : Cambridge University Press, 2021. P. 553–672. DOI: 10.1017/9781009157896.006.

[33] Meinshausen M., Nicholls Z., Lewis J. et al. The Shared Socio-Economic Pathway (SSP) Greenhouse Gas Concentrations and Their Extensions To 2500. *Geoscientific Model Development*. 2020. Vol. 13, № 8. P. 3571–3605. DOI: 10.5194/gmd–13–3571–2020.

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consistency between the reference period and the projection[35]. In this study, the historical reference series used for scenario construction is taken from Berkeley Earth, which is widely applied in climate monitoring and synthesis products[36].

The projected changes in annual mean surface air temperature for Ukraine relative to a late-19th-century pre-industrial baseline under three SSP pathways are presented Figure 8. In brief:

- SSP1-2.6 represents a low-forcing pathway consistent with rapid mitigation, where warming stabilizes at comparatively lower levels by 2100;
- SSP2-4.5 depicts an intermediate pathway with slower emissions reductions and mid-range warming outcomes by the end of the century;
- SSP3-7.0 reflects a high-forcing pathway with continued growth of emissions for the century and correspondingly larger warming by 2100.

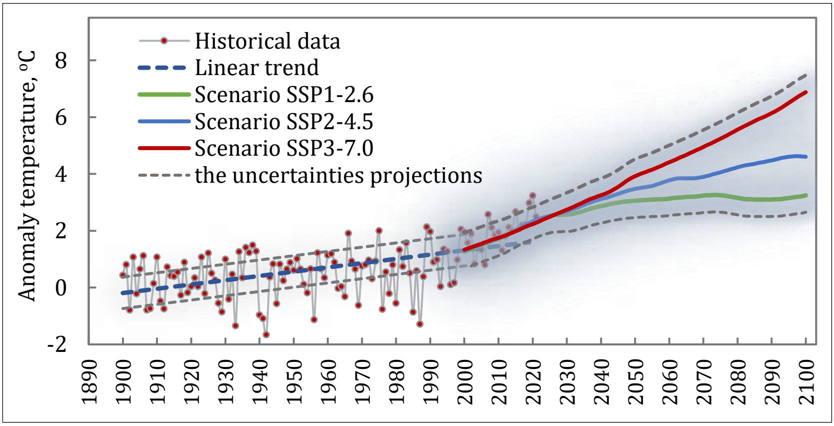

Fig. 8. The annual average surface temperature changes relative to a pre-industrial baseline in the late 19th century in Ukraine (historical data) and the three scenarios of changes (SSP1-2.6, SSP2-4.5, and SSP3-7.0), based on greenhouse emissions scenarios by 2100 (the uncertainties associated with projections)

Source: http://berkeleyearth.org

[35] Krakovska S., Palamarchuk L., Gnatiuk N., Shpytal T. Projections of Air Temperature and Relative Humidity in Ukraine Regions to the Middle of the 21st Century Based on Regional Climate Model Ensembles. *Geoinformatika*. 2018. № 3. P. 62–77. URL: https://www.geology.com.ua/en/7514-2/

[36] Berkeley Earth. URL: http://berkeleyearth.org (accessed on 15 January 2026).

Finally, SSP2-4.5 may be prudently treated as a pragmatic "central" reference, as it approximates a world where mitigation progresses but remains insufficient to limit warming to the lowest range. Accordingly, SSP1-2.6 and SSP3-7.0 define the lower- and higher-end envelopes for a comprehensive risk-based analysis[37].

CONCLUSIONS

This study consolidates long-term meteorological observations to quantify century-scale change in Ukraine's thermal regime and to support climate assessment and decision-making. For 1900–2021, the national mean annual surface air temperature equals 8.6 ± 0.9 °C, rising to 9.5 ± 0.9 °C for 1991–2020. The linear trend reaches 1.31 ± 0.42 °C per century, whereas the most recent 30 years show a much steeper increase of 0.79 ± 0.08 °C per decade, evidencing an acceleration of warming relative to early twentieth-century conditions.

Spatial diagnostics indicate that warming is pervasive but not uniform. Across most of the country, average annual temperature increased by ~1.5–2.0 °C between 1900 and 2021. The strongest changes (2.0–2.5 °C) are detected in parts of northern, northwestern, and eastern Ukraine and in Vinnytsia and Zaporizhzhia oblasts, while comparatively smaller increases (1.0–1.5 °C) occur in the southwest, the south, and areas near the Ukrainian Carpathians. Annual anomalies also confirm the shift toward warmer conditions, with recent decades concentrating on many of the warmest years in the record.

Interannual variability exhibits a clear spatial structure, with larger year-to-year dispersion in cooler northern regions and smaller variability in warmer southern/southwestern areas. The seasonal cycle remains pronounced (summer maxima, winter minima) and is well captured by a compact harmonic representation, supporting the use of compact descriptors (amplitude and phase) in regional diagnostics. Agreement between modeled and observed values is high. Trend significance is assessed with the Mann-Kendall test (95 % level), and national-scale maps are produced using thin-plate spline radial basis interpolation.

Finally, SSP1-2.6, SSP2-4.5, and SSP3-7.0 projections provide a scenario context for interpreting observed change and for communicating plausible futures. Collectively, the results highlight the need for region-specific adaptation

[37] IPCC, 2023: Summary for Policymakers. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change / Core Writing Team, H. Lee and J. Romero (eds.). Geneva : IPCC, 2023. P. 1–34. DOI: 10.59327/IPCC/AR6–9789291691647.001.

and for continued enhancement of station networks and data products to better resolve emerging gradients and extremes relevant to impact nationwide.

SUMMARY

Long-Term Temperature Change in Ukraine (1900–2021): Trends, Variability and Scenarios synthesize a century of instrumental observations to quantify long-term change, interannual variability, and future trajectories of near-surface air temperature across Ukraine. Using monthly mean temperature series from 45 meteorological stations ($\Omega_{1900–2021}$) spatially averaged nationally, the study diagnoses annual, monthly, and seasonal behaviour while acknowledging historical discontinuities and recent data constraints in parts of eastern and southern Ukraine. Trend robustness is assessed with least-squares regression and the Mann-Kendall test, and spatial fields are mapped with thin-plate spline radial-basis interpolation in QGIS/SAGA GIS. Results show an accelerated warming signal: national mean annual temperature for 1900–2021 is 8.6 ± 0.9 °C, increasing to 9.5 ± 0.9 °C for 1991–2020, with a centennial trend of 1.31 ± 0.42 °C per 100 years and a recent rate of 0.79 ± 0.08 °C per decade. Warming is spatially heterogeneous, reaching ~2.0–2.5 °C in parts of northern, northwestern and eastern Ukraine, versus ~1.0–1.5 °C in the southwest, south, and areas adjacent to the Carpathians. Variability is seasonally structured, with maxima in January-February and minima in summer, implying differentiated risks for energy demand, phenology, and thermal extremes. The synthesis offers a baseline for monitoring extremes and prioritising sectoral adaptation measures. Finally, Berkeley Earth-based SSP1-2.6, SSP2-4.5 and SSP3-7.0 projections provide a scenario envelope for 21st-century warming to support risk-informed adaptation and climate-impact planning.

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