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A century-long tendency of change in surface air temperature on the territory of Ukraine

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Early historical meteorological observations of air surface temperature on 11 meteostations in Ukraine (since 1808) were analyzed. However, since a larger number of stations have time series of temperature starting in 1821—1825, for more reliable estimates of the linear trend, the period 1824—2021 was required. The trend is 0.78 °C per 100 years for this period.

According to the analysis of meteorological data, the average annual surface air temperature on the territory of Ukraine in 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. The temperature in Ukraine exhibited an increase of 1.31±0.42 °C per 100 years during 1900—2021. Over the last 30 years, a more pronounced increase in annual surface air temperature, by 0.79±0.08 °C per decade, was observed.

Changes in the temperature regime exhibit spatio-temporal patterns. In most parts of Ukraine in 1900—2021, a temperature increase is within 1.5—2.0 °C per 100 years. Simultaneously, some parts of northern, northwestern, and eastern regions, as well as the Vinnytska and Zaporizhzhska oblasts, are characterized by more intense warming, reaching 2.0—2.5 °C per 100 years, 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 per 100 years.

Temperature anomalies from 1900 to 2021 indicate the lowest annual averages occurred in 1933, 1956, 1976, 1985, and 1987, while the highest annual averages were observed in 2007, 2015, 2019, and 2020.

Between 1900 and 2021, the average monthly air temperature in Ukraine substantially increased in colder months (from October to March), ranging from 0.7 to 2.0 °C per century. Simultaneously, warmer months (from April to September) saw an elevation ranging from 1.0 to 1.9 °C per century. In the 1991—2020 norm, an overall warming trend of 0.5—1.3 °C per decade was observed. Notably, January showed a slight decrease in the warming rate, with a trend value of –0.1 °C per decade.

An indicator of the seasonality of climatic conditions is the amplitude of surface air temperature (*A*). In Ukraine, the average amplitude A was 12.7±1.1 °C from 1900 to 2021 and 12.5±0.8 °C from 1991 to 2020. Analysis of the temperature amplitude over the 20th century and the early 21st century revealed a general tendency of decreasing *A* values (the trend is –0.5 °C per 100 years), primarily due to warming in the colder months. However, from 1991 to 2020, the trend in *A* values was only –0.001 per decade, attributed to a significant temperature rise during the warmer months.

Based on the analyses of the Johansson-Ringleb continentality indices in Ukraine,

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the indices' values were determined to be 59.3±3.7 for the period spanning from 1900 to 2021, and 59.0±3.4 from 1991 to 2020. An overarching trend indicates a decrease by 0.4 % per 100 years. However, from 1991 to 2020, a contrasting pattern emerged, revealing an increase by 6.4 % per decade.

The three scenarios of annual average surface temperature changes in Ukraine (SSP1-2.6, SSP2-4.5, and SSP3-7.0) relative to pre-industrial levels in the late 19th century, based on greenhouse emissions scenarios by 2100, are discussed.

Key words: average annual and monthly surface air temperature, temperature amplitude, continentality indices, temperature anomalies, scenarios of annual average surface temperature changes.

Introduction. Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming. The global mean temperature in 2022 is estimated to be 1.15±0.13 °C above the 1850—1900 pre-industrial average. The eight years from 2015 to 2022 will likely be the eight warmest years on record [WMO, 2022]. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use, lifestyles, and patterns of consumption and production across regions [IPCC, 2023]. Warming anomalies in a large area have become typical manifestations of climate change in most parts of the World and Europe in particular [Hegerl et al., 2018; Krauskopf, Huth, 2020; Twardosz, Kossowska-Cezak, 2021; Twardosz et al., 2021; Nita et al., 2022].

Amidst the backdrop of climate change, distinct patterns of temperature variations throughout the seasons [Pezzulli et al., 2005; Barbosa, 2009; Manabe, 2011; Twardosz et al., 2021] and changes in the amplitude of the annual cycle [Stine et al., 2009] have been identified. One of the modern regional features of climate change throughout the 20th century and at the beginning of the 21st century is the spatial-temporal transformation of the amplitude of the seasonal temperature variation due to sufficiently significant warming, which led to a decrease in the continentalization [Ciaranek, 2014; Vilcček et al., 2016; Szabó-Takács et al., 2015; Boychenko et al., 2018].

Ukraine's climate has been changing in unison with global processes [Voloshchuk, Boychenko, 2003]. Due to climate changes against the background of rising average annual temperatures and changes in the spatial distribution of precipitation, the frequency of extremely high temperatures in the east of Central Europe, including Ukraine, is increasing, and the frequency of extreme cold is decreasing. Over the past twenty years, every year in Ukraine has been warmer than the long-term average, and 2020 became the hottest year in Europe and Ukraine, exceeding the 1961—1990 average by 2.8 °C [Wilson et al., 2021]. However geographical zonation and atmospheric circulation dominate in shaping the random component of the interannual variability of the climatic field of temperature in Ukraine [Lipinskyy et al., 2003].

There is currently a strong evidential base for understanding future climate change in Ukraine, developed through successive stages of modeling studies included in the assessment reports of the Intergovernmental Panel on Climate Change (IPCC), the latest of which is the Sixth Assessment Report (AR6) [IPCC, 2023] as well as regional modeling studies such as EURO-CORDEX [Jacob et al., 2014, 2020].

To assess relevant regional climate changes, it is advisable to analyze a long-term series of meteorological observations because the long-term datasets establish a baseline for climate research from a historical perspective. They provide a historical context against which current climate conditions can be compared, helping identify fluctuations and changes in the Earth's climate system [Oliver, 2005].

In this study, we introduce a long-term surface air temperature analysis for the territory of Ukraine. We use three temperature datasets: the historical (since 1808) dataset (for 11 weather stations), the long-time (1900—2021) dataset (for 35 weather stations), and temperature data from Berkeley Earth source (which are commonly used in climate bulletins and scientific assessments) [Rohde, Hausfather, 2020; Climate …, 2024].

In summary, for the territory of Ukraine, our study aims to analyze early instrumental meteorological observations regarding the surface air temperature from 1808 to 2021; long-term changes in average annual surface air temperature; the relationships between interannual variations, linear trend coefficients, and long-term annual means of surface air temperatures; the annual cycle of surface air temperature; long-time changes in the thermal continentality index; scenarios of warming in Ukraine.

This study complements previous research for other datasets and periods [Voloshchuk, Boychenko, 2003; Boychenko, 2008; Boychenko et al., 2016, 2018].

Materials and Methods. The research was based on an analysis of changes in long-term average annual surface air temperature in Global land, North Hemisphere, Europe, and Ukraine, namely:

- average monthly surface air temperatures for the territory of Ukraine. These were calculated by averaging data from 45 weather stations (weather data set $\Omega_{1900—2021}$) for the period from 1900 to 2021 (Table 1) [Central …, 2023; Open Data-Server, 2023; Climate …, 2023; Weather …, 2023]. The selection criteria for meteorological stations included initiation of observations around 1900, missing observations not exceeding 25 %, and even distribution of stations with elevations above sea level not exceeding 350—400 m. Observational omissions at weather stations in this region were prevalent, notably during the First World Warand the consequent perturbation periodin the former Russian empire (1914—1925) and during the Second World War (1939—1945). Unfortunately, meteorological data for part of the eastern and southern regions is unavailable from 2014 to 2023 due to the ongoing russian aggression;
- early historical meteorological observations of surface air temperature on 11 meteostations (Dnipro, 1833; Kyiv, 1812; Mykolaiv, 1808; Kamianets-Podilsky, 1844; Kherson, 1825; Luhansk, 1937; Lviv, 1924; Odesa, 1821; Poltava, 1824; Simferopol, 1821) since 1808 were selected from the weather dataset (see Table 1);
- average annual surface air temperature anomalies. We calculated thembased on the weather data of the pre-industrial period from 1880 to 1900;
- anomalies of surface air temperatures from 1750 to 2020 based on the Berkeley Earth temperature datasets [Berkeley …, 2023]. Temperatures were reported as anomalies relative to the 1951—1980 average. With global temperature data dating back to 1850, it stands as one of the longest continuous climate records. Some land-only areas even have data extending to 1750, providing insights into historical climate conditions, such as those in Ukraine. The temperature anomaly time series for Ukraine has been converted to absolute values.

The Berkeley Earth group has developed a mathematical framework for generating large-scale averages of temperature changes from weather station data. This mathematical framework enables the inclusion of short and discontinuous temperature records, ensuring that nearly all temperature data can be utilized. The framework incorporates a weighting process that evaluates the quality and consistency of a spatial network of temperature stations, serving as an integral part of the averaging process. Thus, data with varying levels of quality can be incorporated without compromising the accuracy of the resulting reconstructions. The Berkeley Earth averaging process is extendable to spatial networks of arbitrary or locally varying density while preserving the expected spatial relationships.

The selected meteorological stations are shown in Fig. 1.

Furthermore, utilizing empirical data from the Ukrainian network of meteorological observation stations spanning periods 1900—2021 and 1991—2021, we analyzed the spatial-temporal distribution of annual and seasonal surface temperatures. The seasonal course of temperature is well-approximated, and the annual amplitude of seasonal tem-

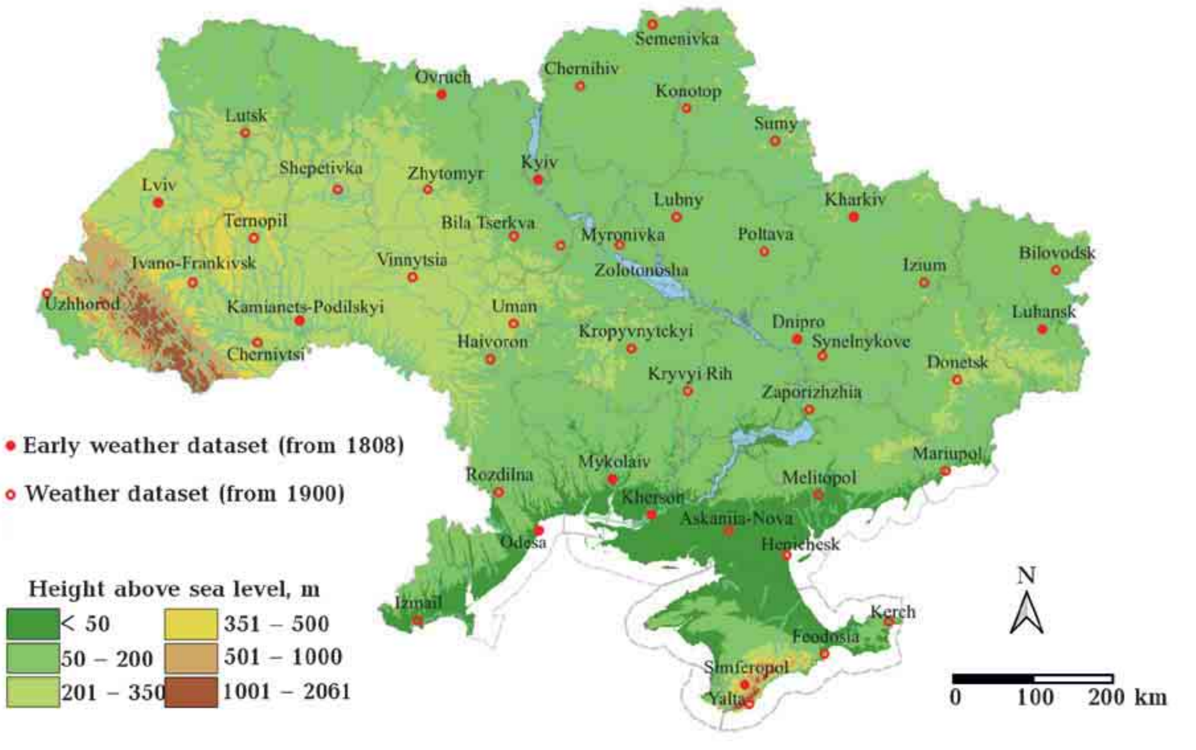


Fig. 1. Map of the selected meteorological stations.

Table 1. Brief metadata of meteorological records

Number	Stations	Altitude, m	Latitude, degrees	Longitude, degrees	Records since	Data gaps for the period 1900—2021, %
33915	Askaniia-Nova	30	46.45	33.88	1910	14
33464	Bila Tserkva	180	49.75	30.18	1872	19
34434	Bilovodsk	75	49.21	39.58	1897	17
33135	Chernihiv	141	51.47	31.28	1883	19
33658	Chernivtsi	246	48.36	25.90	1880	4
34504	Dnipro	143	48.60	35.08	1833	2
33686	Haivoron	175	48.35	29.86	1928	25
33910	Henichesk	15	46.16	34.81	1883	5
33526	Ivano-Frankivsk	280	48.96	24.70	1887	22
33889	Izmail	30	45.36	28.86	1886	22
34415	Izium	78	49.18	37.30	1900	6
33548	Kamianets-Podilskyi	222	48.65	26.58	1844	6
34300	Kharkiv	154	49.96	36.13	1841	2
33902	Kherson	54	46.63	32.61	1825	8
33261	Konotop	149	51.23	33.20	1893	7
33711	Kropyvnytckyi	171	48.51	32.25	1874	2
33791	Kryvyi Rih	124	48.03	33.21	1881	3
33345	Kyiv	166	50.40	30.57	1818	—

Number	Stations	Altitude, m	Latitude, degrees	Longitude, degrees	Records since	Data gaps for the period 1900—2021, %
33377	Lubny	158	50.00	33.02	1892	2
33187	Lutsk	232	50.70	25.33	1892	22
34519	Luhansk	62	48.56	39.26	1837	6
33393	Lviv	319	49.81	23.95	1824	2
34712	Mariupol	70	47.04	37.48	1900	2
34704	Melitopol	34	46.83	35.36	1883	16
33846	Mykolaiv	50	47.03	31.96	1808	1
33466	Myronivka	153	49.66	31.00	1913	14
33837	Odesa	42	46.43	30.76	1821	3
33213	Ovruch	170	51.31	28.78	1894	7
33506	Poltava	160	49.60	34.55	1824	2
33834	Rozdilna	148	46.85	30.08	1925	23
33049	Semenivka	161	52.18	32.58	1927	22
33317	Shepetivka	278	50.16	27.05	1924	22
33275	Sumy	181	50.85	34.78	1896	1
34505	Synelnykove	146	48.40	35.50	1915	3
33415	Ternopil	329	49.53	25.67	1881	12
33587	Uman	216	48.76	30.23	1886	1
33631	Uzhhorod	124	48.63	22.26	1881	11
33562	Vinnytsia	298	49.23	28.46	1900	16
34601	Zaporizhzhia	112	47.80	35.25	1885	6
33325	Zhytomyr	224	50.23	28.63	1886	5
33484	Zolotonosha	96	49.68	32.03	1895	2
33976	Feodosia	26	45.03	35.38	1881	2
33983	Kerch	49	45.37	36.43	1874	2
33946	Simferopol	181	44.7	34.1	1821	3
33990	Yalta	72	44.48	34.17	1881	2

perature variation was objectively calculated using Fourier fitting with a single (annual) harmonic [Von Storch, Zwiers, 1999]:

$$T_m^k \approx T_0^k + a\sin\frac{2\pi(m-0.5)}{12} + b\cos\frac{2\pi(m-0.5)}{12},$$

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

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

$$T_0^k = \frac{1}{12}\sum{}_m T_m^k,\ m = 1, 2, ..., 12,$$

$$A = \sqrt{a^2 + b^2},\ F = \mathrm{arctg}\frac{b}{a}, \qquad (1)$$

where k is the meteorological station number and m is the month number, A and F are amplitude (°C) and the phase (in a unit of m) of seasonal temperature variation.

Also, based on the analyses of the Johansson-Ringleb continentality indices in Ukraine, the indices' values were determined for the period spanning from 1900 to 2021 and from 1991 to 2020 [Johansson, 1931].

The period from 1900 to 2021 was employed to illustrate long-term trends in annual and monthly surface air temperature, providing a baseline against which the significant changes during 1991—2020 were analyzed. Additionally, climatic norms for temperature from 1991 to 2020 were calculated, while norms for the period 1961—1990 were obtained from Climate Cadastre [The Climate …, 2005]. Assessing trends in the seasonal temperature courses involved calculating linear trend coefficients for each month at a given meteorological station and then averaging them over the territory.

The three Shared Socioeconomic Pathways (SSPs) scenarios of annual average surface air temperature changes in Ukraine (SSP1-2.6, SSP2-4.5, and SSP3-7.0) relative to pre-industrial levels in the late 19th century, based on greenhouse emissions scenarios by 2100, were constructed by Berkeley Earth`s data source [Berkeley …, 2023].

The trends were determined using linear least squares regression lines. The Mann-Kendall nonparametric test was used to assess the statistical significance of temperature trends (with a significance level of 95 %). The research results are based on data processed using standard methods of statistical analysis for meteorological information [Von Storch, Zwiers, 1999]. Statistical analysis and graphical representation were conducted using MS Excel and XLSTAT software packages.

QGIS and SAGA-GIS software were used to develop maps. The radial basis function with thin plate spline was applied for spatial interpolation of meteoparameters. It is widely used to interpolate weather data from meteorological station networks, especially in the case of sparse input point distribution [Boer et al., 2001; Smith et al., 2017].

Results. ***Early instrumental meteorological observations in the territory of Ukraine regarding the surface air temperature since 1808.*** Climatic analyses require homogeneous data and long-term series, which is particularly important for climate change and variability [Oliver, 2005]. Unfortunately, most long-term climatological time series have been affected by several non-climatic factors that make these data unrepresentative for analysis of the actual climate variation occurring over time. These factors include, in particular, changes in observing instruments and practices, station locations, and formulae used to calculate derived quantities. The missing periods in the meteorological data can be due to various reasons, including gaps in record-keeping, data loss, or perhaps the absence of consistent observations during those years, and social factors such as wars, post-war periods, revolutions, etc.

Climate datasets based on more or less systematic instrumental observations date back to the middle of the 19th century, but scientific measurements of meteorological parameters began even earlier, in the 17th century [Camuffo, Bertolin, 2012; Pfister et al., 2019; Brönnimann et al., 2019; Brugnara et al., 2020].

The Central England temperature series is one of the longest continuous temperature records in the world from the year 1659 to the present. The monthly mean surface air temperatures of the Midlands region (England) record is a meteorological dataset published by G. Manley (1953) and subsequently extended and updated in 1974 [Manley, 1974] and the time series were homogenized [Parker, 2009]. This record represents the longest series of monthly temperatures since 1659 [Camuffo, Bertolin, 2012; Met Office …, 2023] and the series of daily temperatures since 1772 [Camuffo et al., 2020a], and it is a valuable dataset for meteorologists and climate scientists.

Another the earliest temperature series in Paris from 1658, taken by the astronomer Ismaël Boulliau and the botanist doctor Louis Morin is made available at daily resolution after careful work of homogenization and correction [Rousseau, 2013; Camuffo et al., 2020b]. Johann Jakob Scheuchzer's temperature records from Zurich, starting in 1718, represent one of the earliest digitized time series of temperature measurements [Brugnara et al., 2020]. Long-term datasets have been made in Uppsala, Sweden, since 1722, and a complete series of air temperatures have been reconstructed and homogenized [Bergström, Moberg, 2002].

Early meteorological observations on the territory of Ukraine were started in the middle of the 18th century by scientific groups within Universities. According to the restored data, the first observations (air temperature and atmospheric pressure) were recorded in Kharkiv in 1738—1741, in Snovsk (near Chernihiv) in 1769—1782, and in Kyiv in 1770—1771 [History ..., 1968; Matushevsky et al., 1970]. At the beginning of the 19th century, several amateur weather stations appeared (Kyiv, 1804; Berdychiv, 1814; Odesa, 1821; Poltava, 1824; Mykolaiv, 1824; Kherson, 1825).

Although meteorological data in Kyiv dates back to 1770, sub-daily data is available only from 1812 to 1841, with missing periods (for example, 1846—1853). Also, in Kharkiv, regular archival data is available starting from 1840—1841 [History ..., 1968].

The first observatories commenced in Luhansk in 1836 and Kharkiv in 1839. Note that this study uses observational data from the Kherson station in 1825, but records as early as 1808 have been reconstructed [Skrynyk et al., 2021]. Subsequently, in the 20—40 s of the 19th century, Dnipropetrovsk (Dnipro), Kamianets-Podilskyi, and Poltava weather stations were also opened (see Table 1).

Unfortunately, since 2014, observations have been interrupted or unavailable for most of the territory of the occupied Donetsk and Luhansk regions and Crimea. In Febru-

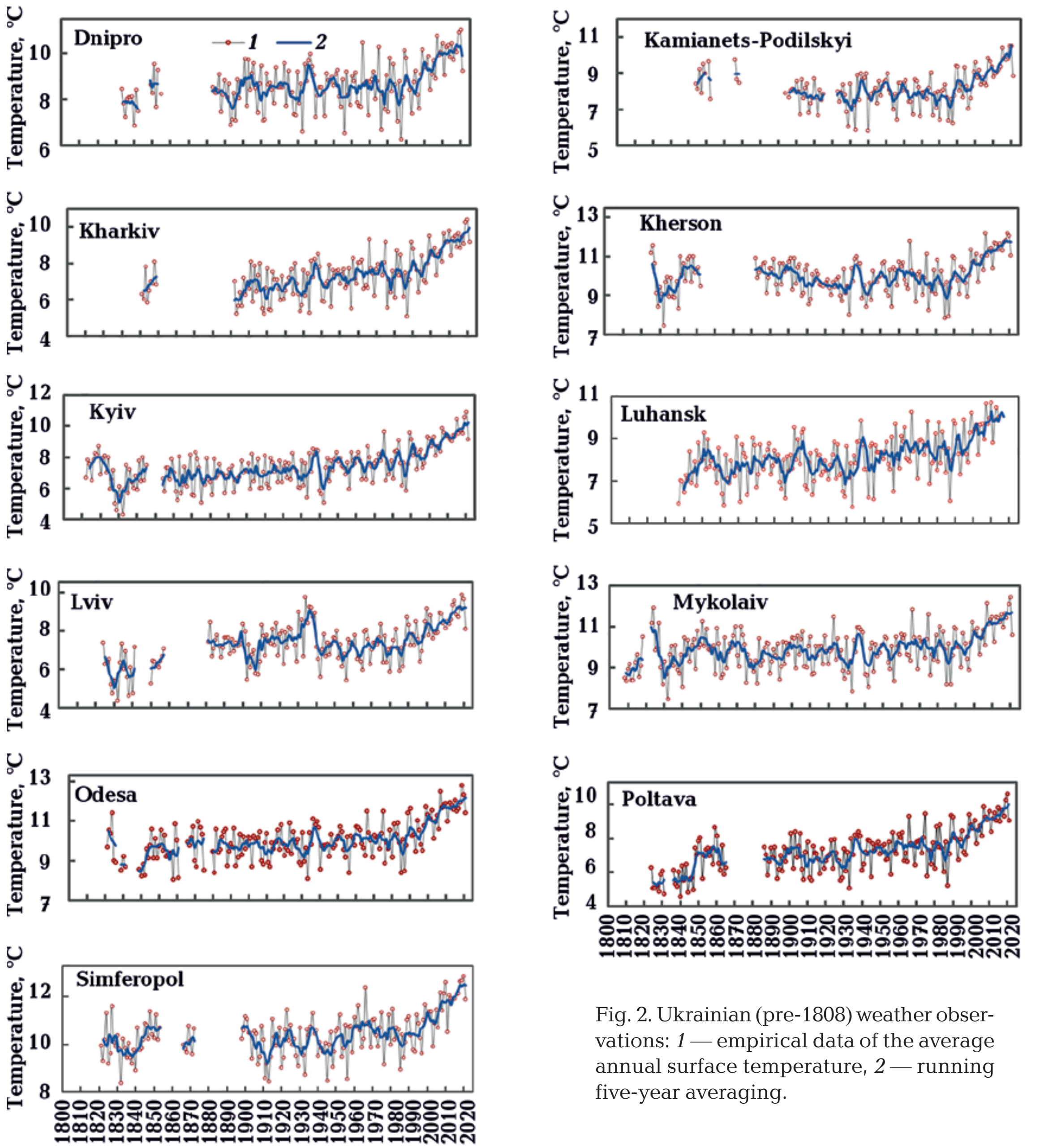


Fig. 2. Ukrainian (pre-1808) weather observations: *1* — empirical data of the average annual surface temperature, *2* — running five-year averaging.

ary 2022, some observations were lost due to the occupation of the southern regions of Ukraine, the destruction of weather stations as a result of the actions of the occupiers, and as a result of the blackout.

The average annual surface temperature long-term time series, recorded at the weather stations in Ukraine from 1808 to 2021, are shown in Fig. 2.

The long-term average annual surface temperature time series, recorded at the weather stations, and an averaged time series for Ukraine from 1808 to 2021 are shown in Fig. 3. The warmest years and the coldest years were selected for this period. Anomalously warm or cold years were selected according to the following formula: $T_{warm}(k)>T_{apr}(k)+\sigma$ and $T_{cold}(k)<T_{apr}(k) - \sigma$, where $T_{apr}(k)=0.0062k–3.2948$ is the linear approximation of the average annual temperature, k is a certain year, σ is the temperature standard deviation. As we can see, the largest number of the warmest years is typical for the 19th century, as well as for the end of the 20th century and the beginning of the 21st century, while the coldest years are observed in the 20th century.

The main statistical characteristics for these time series of the average annual temperature are given in Table 2. However, since a larger number of stations have time series of temperature starting in 1821—1825, the period 1824—2021 is required for more reliable estimates of the linear trend. As we can see in this table, the trend is 0.78 °C per 100 years for this period. This table also presents for comparison the main statistical parameters for the 20th century.

Long-time changes of average annual surface air temperature in Ukraine from 1900 to 2021. Since 1880, the annual global surface air temperature has fluctuated, showing an overall signification upward tendency [IPCC, 2023]. The annual surface air temperature anomaly was at its highest point in 2020, at 1.65 degrees above average [Climate …, 2024]. Anomalies in surface temperature in Ukraine followed a similar trend over the same period.

Meteorological observations of ground-level air temperature in Ukraine have long-term records, spanning over 100—120 years, encompassing 45 stations (see Table 1). However, observations from the beginning of the 19th century were conducted only at 11 of these stations (see Fig. 3). As seen in Fig. 4, relatively regular instrumental recordings evenly distributed across the territory of Ukraine started from 1890 to 1900. Therefore, to obtain reliable (representative) statistical estimates regarding changes in surface air temperature, we shall use observational data from 1900 for further analysis. The average annual temperature change in Ukraine from 1808 to 2021 is 0.43 °C per 100 years.

Fig. 5 shows the long-term average annual

Table 2. Average annual temperature (<*T*>, °C), standard deviation (±σ, °C), and linear trend coefficients ($T_{rn}\{T\}$, °C per 100 years) for weather stations with the longest observation records in Ukraine

Parameters	Dnipro	Kyiv	Kamianets-Podilskyi	Kharkiv	Kherson	Lviv	Luhansk	Mykolaiv	Odesa	Poltava	Simferopol	All stations
1824—2021												
<*T*>	8.7	7.4	8.2	7.4	10.0	7.3	8.1	10.0	10.0	7.3	10.4	**8.6**
±σ	1.0	1.2	0.9	1.2	0.9	1.1	1.1	0.9	1.0	1.3	0.9	**0.9**
$T_{rn}\{T\}$	0.76	1.38	0.44	1.49	0.42	1.06	0.99	0.54	0.95	1.44	0.66	**0.78**
1901—2000												
<*T*>	8.5	7.5	7.9	7.2	9.8	7.4	8.2	9.9	10.0	7.3	10.3	**8.5**
±σ	0.9	1.0	0.8	1.0	0.8	0.9	1.0	0.8	0.8	1.0	0.8	**0.8**
$T_{rn}\{T\}$	0.04	1.26	0.43	1.17	0.16	0.11	1.02	0.37	0.70	1.10	0.74	**0.63**

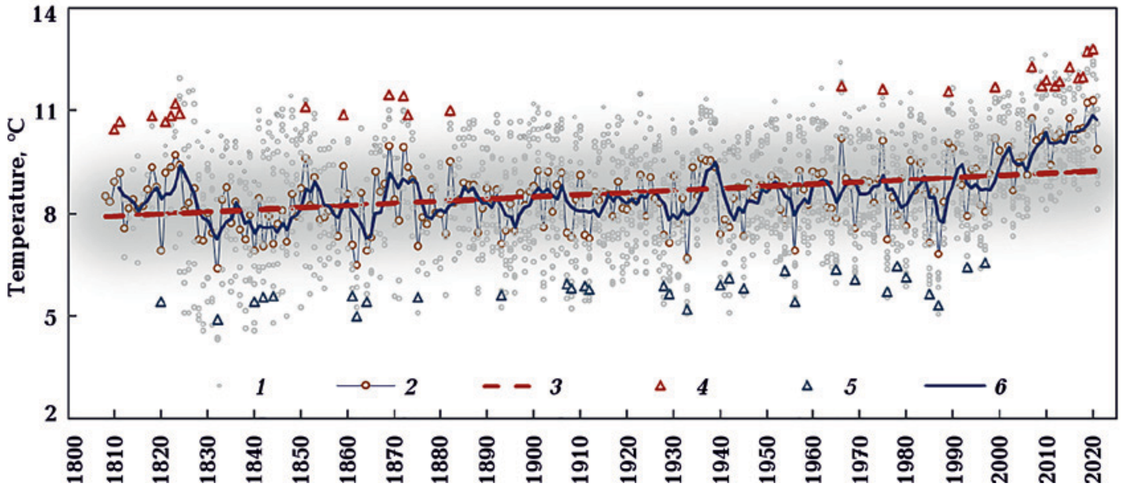


Fig. 3. Average annual surface air temperature: the weather stations data (*1*), the averaged time series (*2*), and the linear trend for Ukraine (*3*) for the period from 1808 to 2021 (*4* is the warmest years; *5* is the coldest years). Statistically significant trends (σ < 0.05).

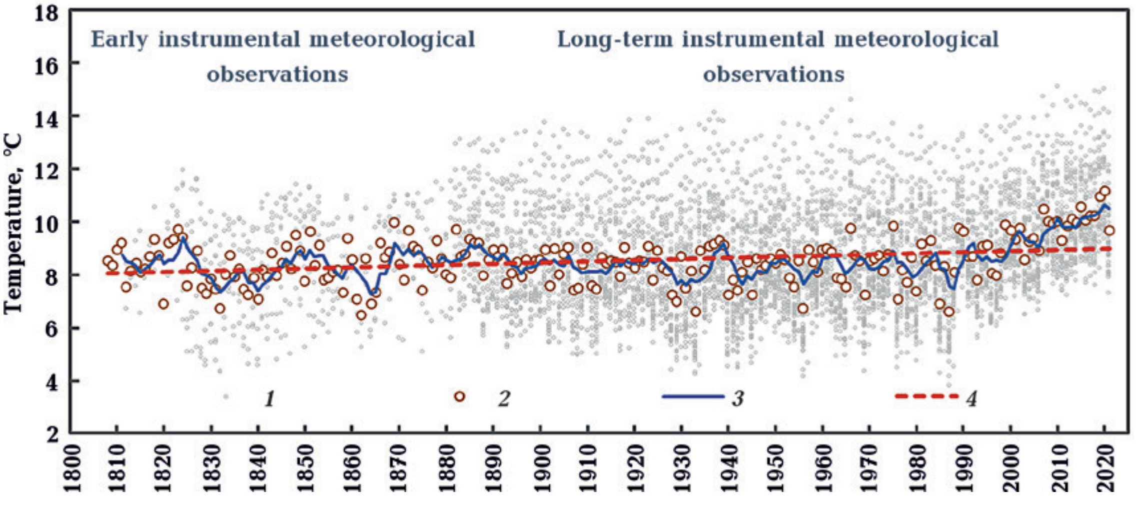


Fig. 4. Long-time average annual surface air temperatures (*1* — time series, recorded at 45 weather stations; *2* — averaged time series; *3* — five-year moving averages; *4* — the linear trend) in Ukraine for the period from 1808 to 2021. Statistically significant trends (σ < 0.05).

surface air temperatures in Ukraine from 1900 to 2021. According to the analysis, the average annual surface air temperature in Ukraine in 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 1961—1990 was 8.4±0.9 °C. As indicated by Fig. 5, the temperature increased at 1.31±0.42 °C per 100 years in 1900—2021. It is 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 the climatic norm for 1961—1990, which showed a decrease (–0.02±0.15 °C per decade).

The spatial distribution of averaged annual surface air temperature and corresponding trends in Ukraine from 1900 to 2021 are shown in Fig. 6.

The climate of Ukraine is shaped by the interplay of various external and internal factors [Lipinskyy et al., 2003]. Global influences

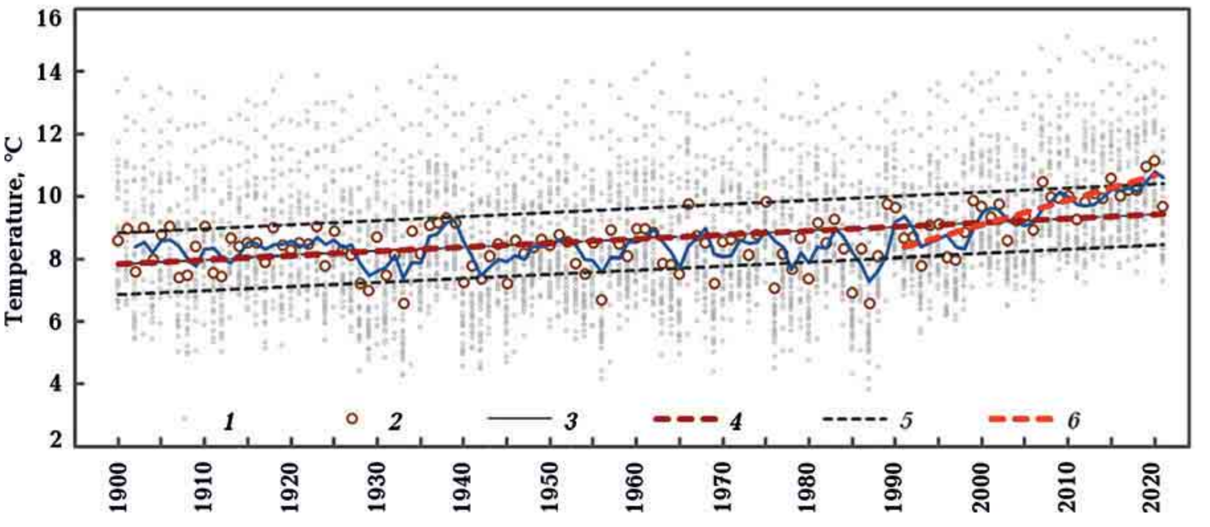


Fig. 5. Long-term average annual surface air temperatures (*1* — time series, recorded at 45 weather stations; *2* — averaged time series; *3* — five-year moving averages; *4* and *6* — linear trends for 1900—2021 and 1991—2020, respectively; *5* — the standard deviation (±σ)) on the territory of Ukraine for the period from 1900 to 2021. Statistically significant trends (σ < 0.05).

include the planet's spatial orientation and the influx of solar electromagnetic radiation. Zonal factors involve the latitudinal characteristics of heat exchange 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, water bodies, vegetation, and other elements, shape the microclimatic characteristics in specific areas.

Changes in the temperature regime exhibit spatial-temporal peculiarities in Ukraine (see Fig. 6). A temperature increase 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 latitudinal features of global warming and the generally continental nature of the climate, along with regional features of atmospheric circulation [Voloshchuk, Boychenko, 2003; Boychenko, 2008].

The average annual surface air temperature anomalies on the territory of Ukraine for the period 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 multi-annual average or the climatic norm. It should be noted that the approach to the estimated anomalies from the multi-annual averages of global mean temperature can be used for monthly averages, as well [State …, 2021; Climate …, 2024].

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 ($\Delta T = T_{year} – \langle T_{<1880–1990>} \rangle$). Temperature anomalies from 1900 to 2021 indicate the lowest annual averages in 1933, 1956, 1976, 1985, and 1987 (ΔT=–0.68±0.54 °C), while the highest annual averages were observed in 2007, 2015, 2019, and 2020 (ΔT=0.74±0.63 °C) (Fig. 7). In the recent decade, there has been a significant increase in temperature in Ukraine, as well as globally.

The analysis of the relationships between inter-annual variations, linear trend coefficients, and long-term annual means of surface air temperatures. The analysis of

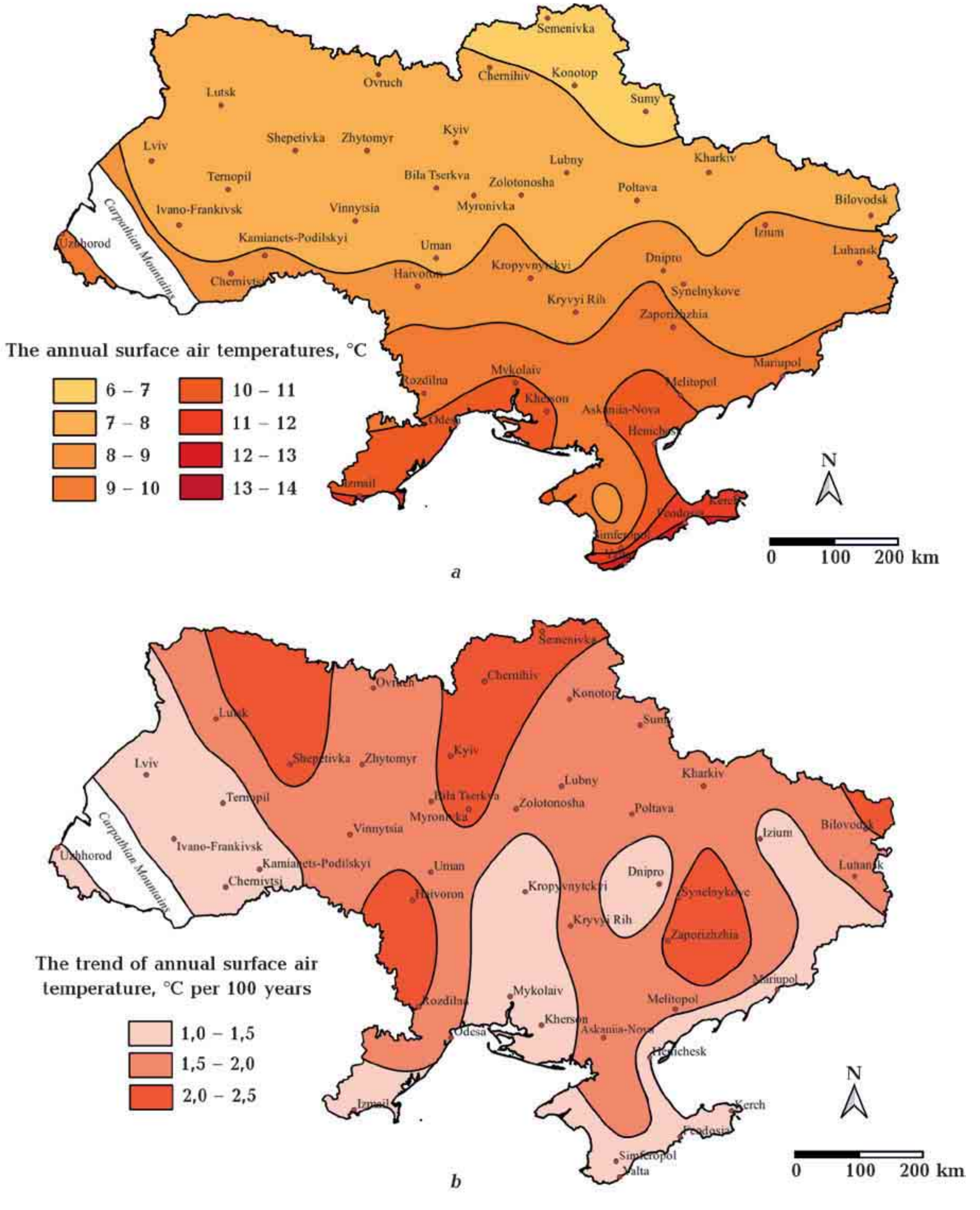


Fig. 6. The spatial distribution of averaged annual surface air temperature (*a*) and corresponding trends (*b*) in Ukraine from 1900 to 2021.

the relationship between inter-annual variations of surface air temperatures var{*T*} (root-mean-square error) and their long-term annual means avr{*T*} for the meteostations in Ukraine (1900—2021) found maximum var{*T*} values were characteristic in areas with low

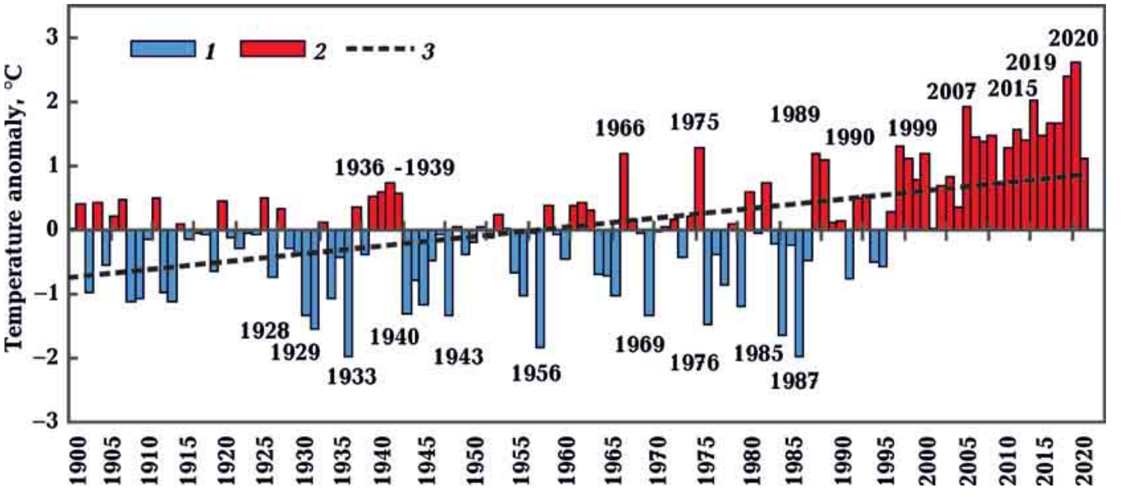


Fig. 7. The average annual surface air temperature anomalies (*1* — the lowest annual average, *2* — the highes tannual average, *3* — the linear trend) in Ukraine from 1900 to 2021.

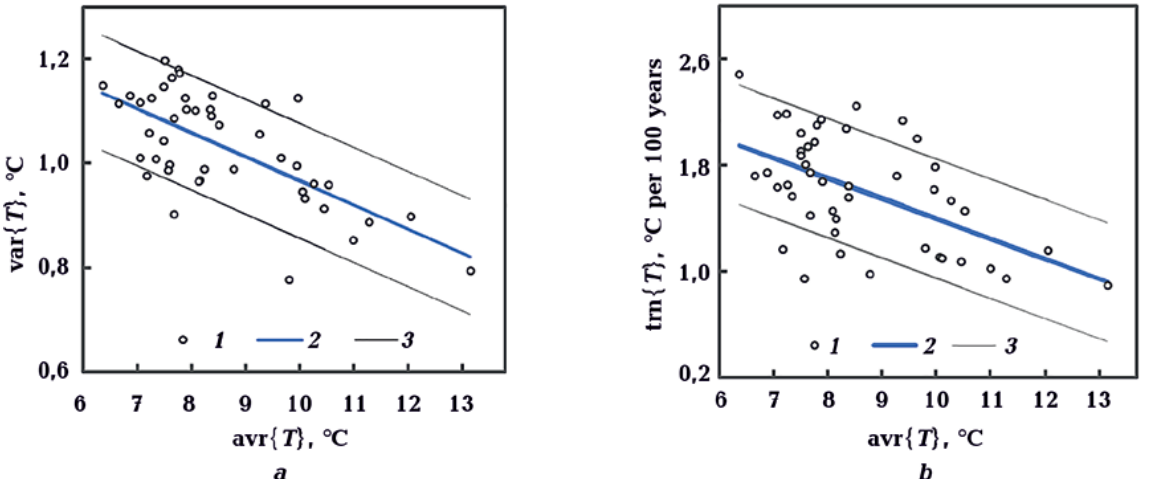


Fig. 8. Comparison of the inter-annual variations values var{*T*} (*a*) and linear trend coefficients trn{*T*} (*b*) with long-term annual means of surface air temperature avr{*T*} for the meteostations in Ukraine with long-time data from 1900 to 2021 (*1* — data, *2* — linear regression, *3* — ±σ).

avr{*T*}, i.e., the northwestern, northern, and northeastern regions. Minimum var{*T*} values were characteristic for areas with high avr{*T*}, which are typical for the southern, southwestern, and southeastern regions of Ukraine.

Therefore, for each degree of annual mean surface air temperature avr{*T*}, the variance var{*T*} changes by approximately –0.05 °C from north to south (Fig. 8, *a*). The relationships between the variance and annual mean air temperature confirm that the geographical zonation and atmospheric circulation dominate in shaping the random component of the inter-annual variability of the climatic field of temperature in Ukraine [Lipinskyy et al., 2003].

When analyzing the relationship between the coefficients of linear trends in the annual mean of surface air temperatures trn{*T*} and their long-term values avr{*T*} for 1900—2021, it was established that the highest values of trn{*T*} were characteristic in northern, northwestern, and northeastern regions. Slightly lower — in southern, southwestern, and southeastern regions of Ukraine. Thus, for each degree of annual mean surface air temperature avr{*T*}, the warming trend trn{*T*} decreases from north to south by 0.15 °C

(Fig. 8, *b*). The similar relationships were obtained early for the period from 1900 to 1990 [Voloshchuk, Boychenko, 2003; Boychenko, 2008]. The current study used more stations for the period from 1900 to 2021, and the gaps in the observations were no more than 25 %.

The intensification of warming towards higher latitudes in the territory of Ukraine is a feature of the latitudinal distribution of warming in the Northern Hemisphere [Voloshchuk, Boychenko2003; Boychenko, 2008].

The annual cycle of surface air temperature in Ukraine. The seasonal course of the surface air temperature in Ukraine has characteristic features of the temperate latitudes [Lipinskyy et al., 2003]. On average, the maximum temperature in Ukraine is observed in summer (from 18.9 to 20.9 °C), and the minimum — in winter (from –4.1 to –1.6 °C). In the transitional seasons, the average temperatures are from 1.3 to 15.2 °C (spring) and from 15.1 to 3.1 °C (autumn). The annual cycle of averaged time series of surface air temperature for the $\Omega_{1900-2021}$ weather dataset and their approximation in Ukraine are shown in Fig. 9.

The seasonal course of temperature T_m is quite well approximated by using Fourier fitting of a single (annual) harmonic (1) [Climate ..., 2024]:

$$T_m = 8.6 + (-3.74)\sin\left(\frac{2\pi(m-0.5)}{12}\right) + $$
$$+(-12.10)\cos\left(\frac{2\pi(m-0.5)}{12}\right),$$
$$A = 12.7 \pm 1.1\,°\mathrm{C} \text{ and } F = 1.27 \pm 0.07, \quad (2)$$

where A and F are the amplitude and the phase of seasonal temperature variation by (1).

The comparison of the model monthly temperatures with their actual values showed that the reliability of the linear regression (R^2) is 0.97—0.99.

The spatial distribution of average monthly surface temperature (in January, April, July, and October) in Ukraine has zonal differences shown in Fig. 10.

The seasonal distribution of the temperature root-mean-square errors, as a characteristic of the variability of weather conditions, showed a pronounced maximum in the cold period of the year, especially in January and February (3.2—3.5 °C), and a minimum in the warm period, especially in the summer (1.6—1.7 °C). Seasonal variation of the temperature root-mean-square errors in Ukraine in 1900—2021 is shown in Fig. 11.

Amidst the backdrop of climate change, distinct patterns of temperature variations throughout the seasons have been identified [Pezzulli et al., 2005; Barbosa, 2009; Manabe, 2011; Boychenko et al., 2018; Twardosz et al., 2021]. From 1900 to 2021, the average monthly temperature in Ukraine showed a pronounced rise in the colder months (October to March), ranging from 0.7 to 2.0 °C per century and the warmer period (April to September) experienced an increase from 1.0 to 1.9 °C per century.

Analysis of linear trends of the surface air temperature for several 30-year periods (meteorological norms) in Ukraine indicates certain differences (Fig. 12). So, for example, the 1961—1990 norm was characterized by a warming in December—March of 0.2—1.0 °C per decade, while in April—November there was even a cooling from –0.2 to –0.8 °C per decade. And for the 1991—2020 norm, a warming of 0.5—1.3 °C per decade was observed. In addition, in January there is a decrease in the rate of warming and the trend value is –0.1 °C per decade.

One of the indicators of climatic conditions' seasonality is the amplitude of surface air temperature. The amplitude of the seaso-

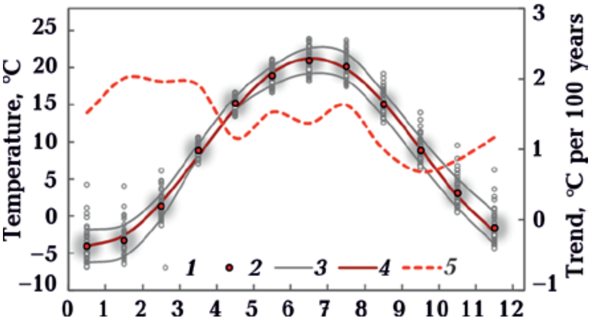
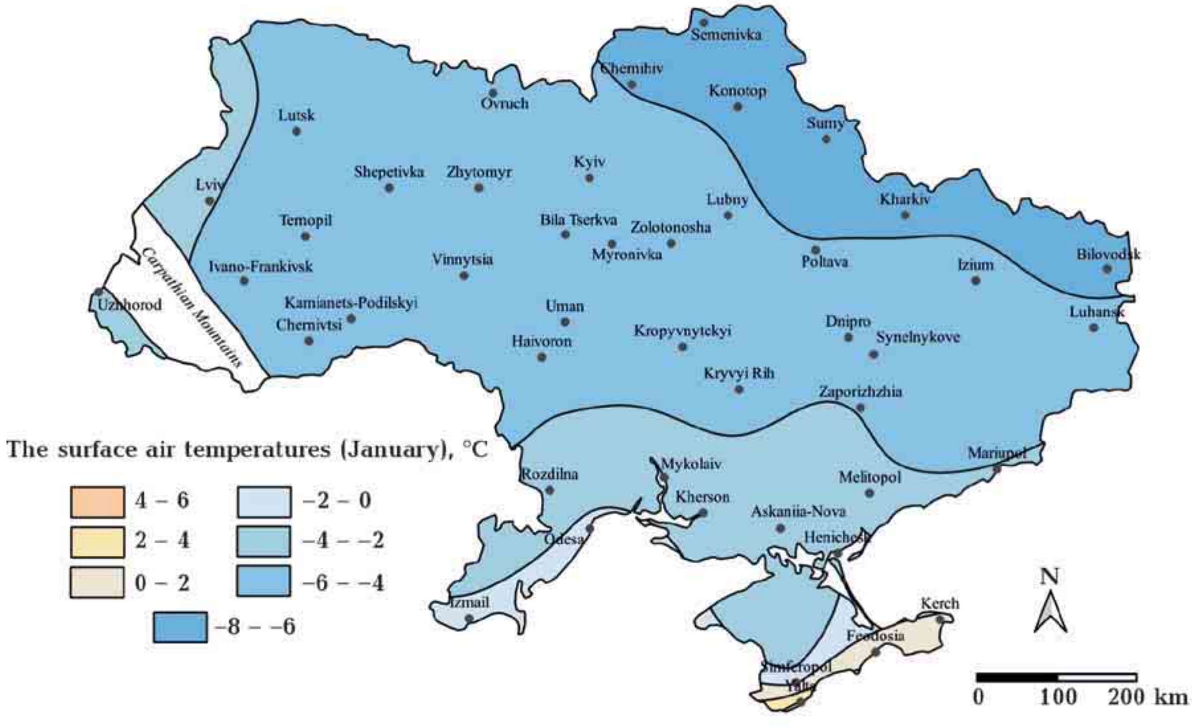
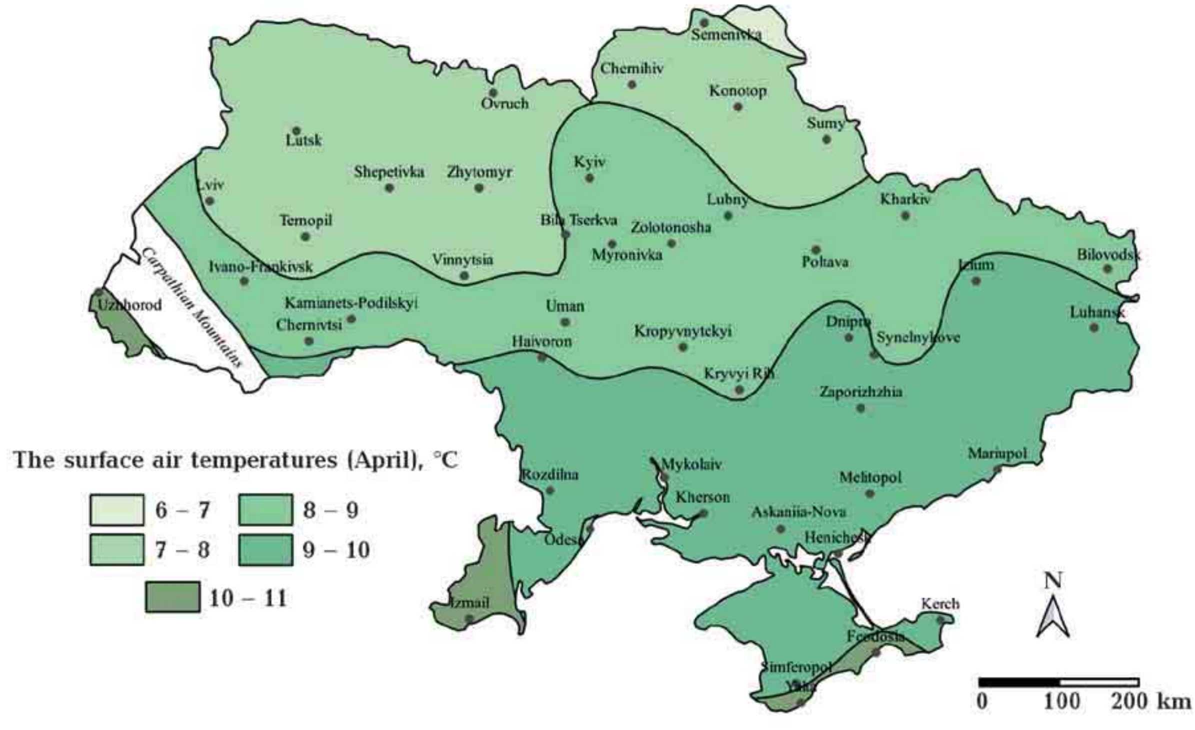


Fig. 9. The annual cycle of surface air temperature (*1* — monthly data, *2* — average values for the $\Omega_{1900-2021}$ dataset, *3* — ±σ, *4* — Fourier approximation) and corresponding trends (*5*) in Ukraine in 1900—2021.





nal temperature (A) was calculated by equation (1) for the weather set from 1900.

The average temperature amplitude in Ukraine is A=12.7±1.1 °C from 1900 to 2021 and 12.5±0.8 °C from 1991 to 2020. The analysis of the seasonal temperature amplitude for the 20th century and the beginning of the 21st century showed a general tendency to decrease A values (the trend is –0.5 °C per 100 years), due more to the warming in the cold period of the year, whereas from 1991 to 2020,the trend in A values was only –0.001 °C

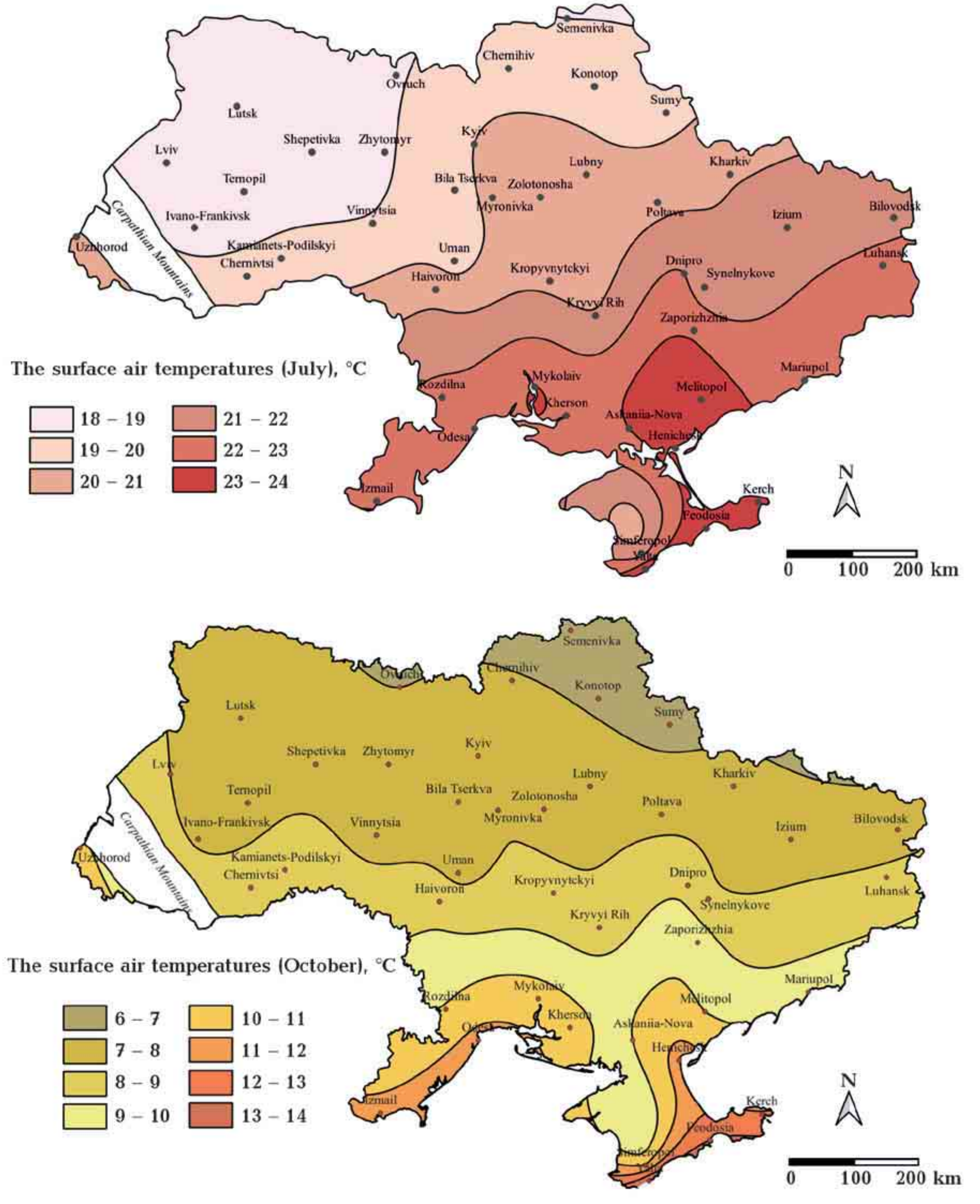


Fig. 10. The spatial averaged monthly surface air temperature in Ukraine in January, April, July, and October (averaged for 1900—2021).

per decade, due to a significant increase in temperature in the warm period of the year.

The variations of the amplitude of the seasonal temperature *A* in Ukraine for periods from 1900 to 2021 are shown in Fig. 13. Some cycles are observed: minimum values in 1915,

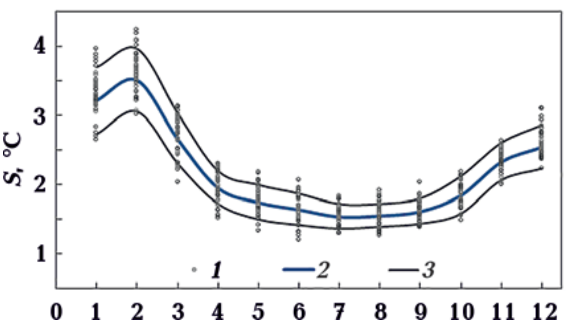


Fig. 11. Seasonal variation of the temperature root-mean-square errors in Ukraine in 1900—2021 (*1* — monthly data for the weather station, *2* — average values, *3* — ±σ).

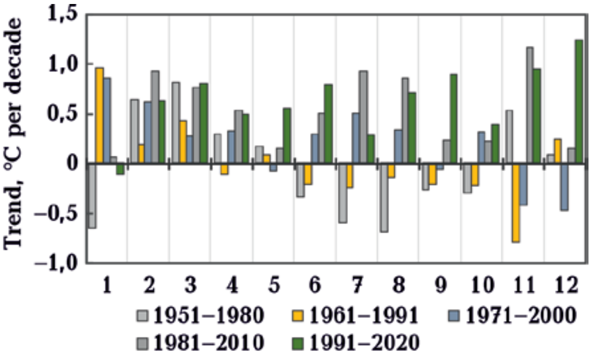


Fig. 12. Seasonal differences in linear trends of the surface air temperature for several 30-year periods on the territory of Ukraine. Statistically significant trends (σ < 0.05).

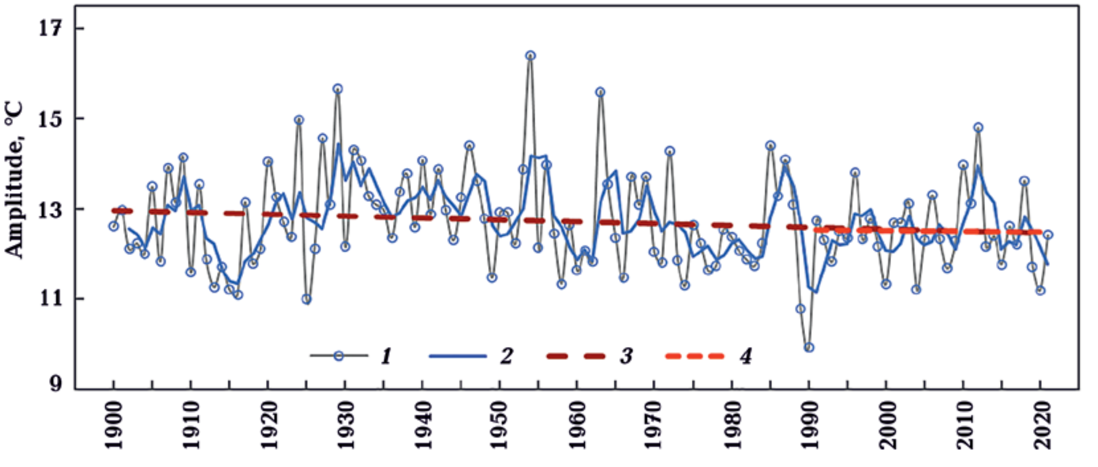


Fig. 13. Long-time changes of the amplitude of the seasonal temperature (*1*) in Ukraine for periods from 1900 to 2021 (*2* — five-year moving averages, *3* and *4* — linear trends for 1900—2021 and 1991 to 2020). Statistically significant trends (σ < 0.05).

1916, 1925, 1990, and 2020 and maximum values in 1902, 1929, 1954, 1963, and 2012.

The spatial distribution of the seasonal air temperature amplitude and their trends in Ukraine from 1900 to 2021 are shown in Fig. 14.

In Ukraine, in the 20th century, against the background of a general increase in the average annual temperature, there was a decrease in the amplitude of its seasonal course (the trend is ~ –0.4 °C/100 years) and it warmed significantly in the cold period, and slightly in the warm period of the year [Voloshchuk, Boychenko, 2003; Boychenko, 2008]. While the temperature amplitude was changed by –0.5±0.2 °C per 100 years from 1900 to 2017 [Boychenko et al., 2018].

The climatic conditions with pronounced seasonality and variability, abnormal summer heat, and regional climate change have a certain negative impact on people's health and comfort. The human comfort (by the bioclimatic index (equivalent-effective temperature)) in Ukraine changed [Boychenko et al., 2021]. The number of days in a year with comfortable thermal conditions for humans tended to increase in 1991—2020. It contributed to more comfortable climatic conditions for the local population. However, over the last couple of decades, especially in the summer, the frequency of anomalously high temperatures has increased.

Long-time changes of the thermal continentality index in Ukraine. The extent of climate

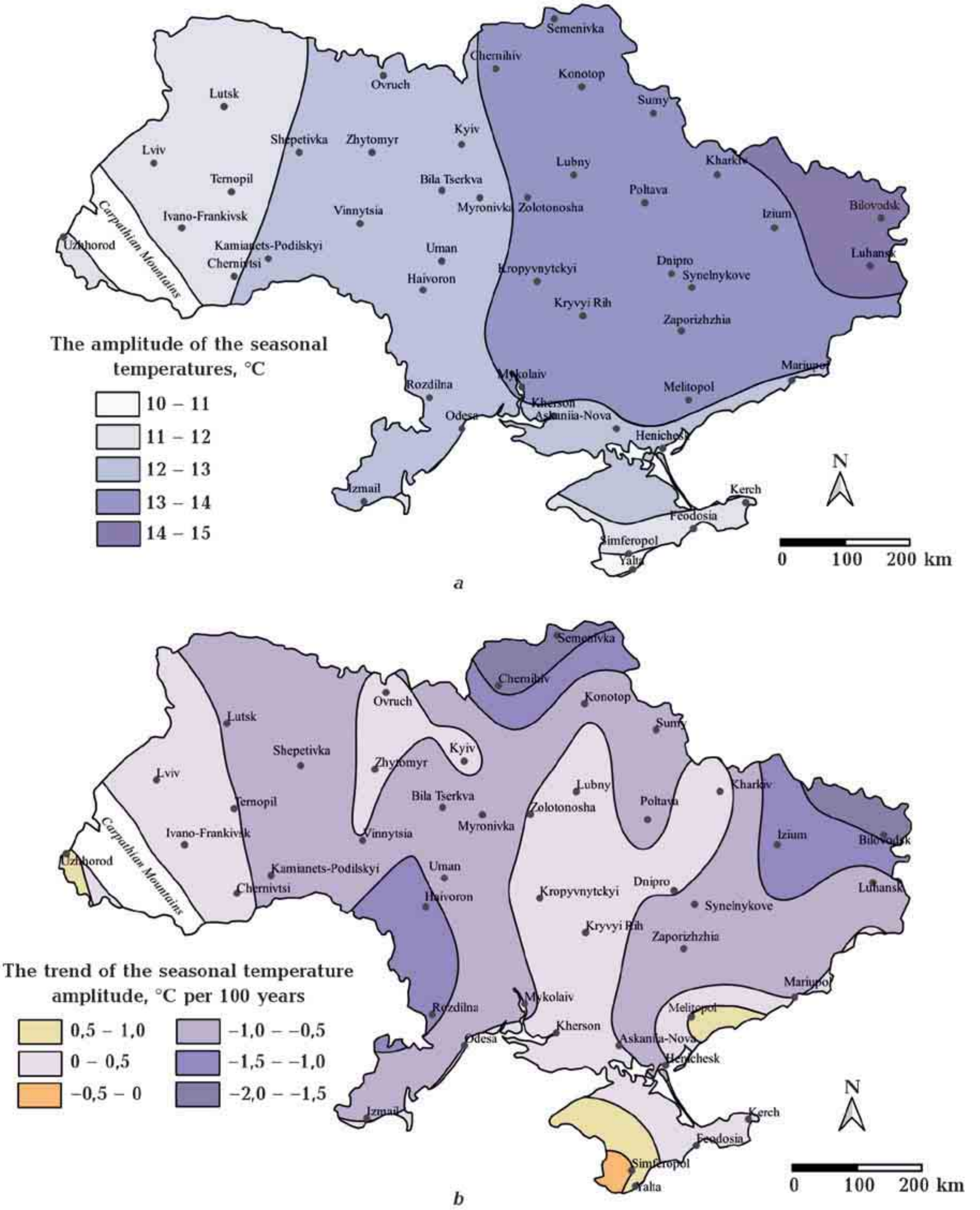


Fig. 14. The spatial distribution of the seasonal air temperature amplitude (*a*) and their trends (*b*) in Ukraine from 1900 to 2021.

continentality is gauged by the corresponding shifts in annual, seasonal, and daily amplitudes of surface air temperature, humidity, cloudiness, wind speed, precipitation variability, and other related factors [Oliver, 2005; Zhang, Gao, 2023]. The space-time dis-

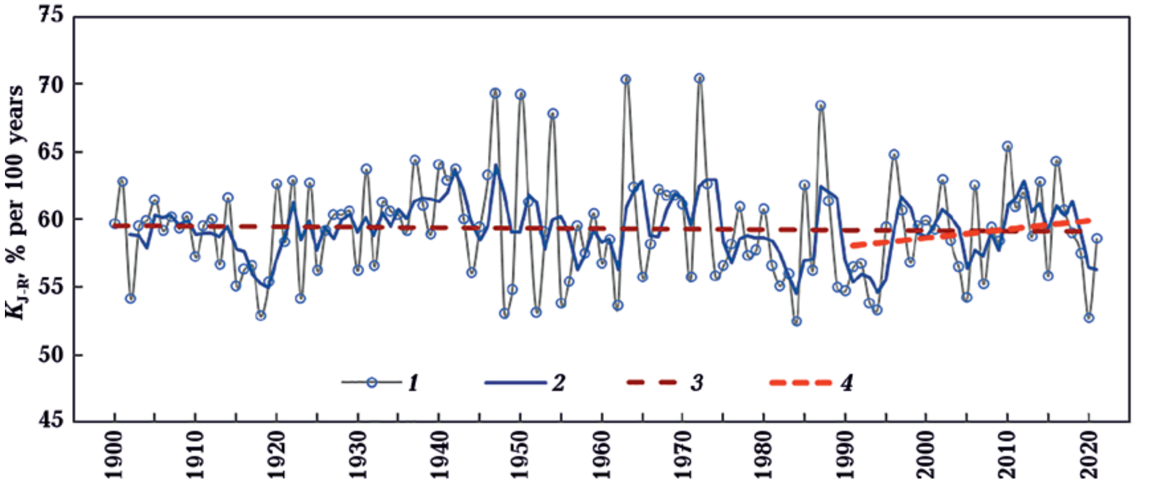


Fig. 15. Long-time changes of the thermal continentality index K_{J-R} (*1*) in Ukraine from 1900 to 2021 (*2* — sliding averaging, *3*, and *4* — linear trend for the period 1900—2021 and 1991 to 2020). Statistically significant trends ($\sigma < 0.05$).

tribution of the surface air temperature on the plain part of Ukraine has features of a temperate continental climate that grows more pronounced towards the north and northeast of the country (deep into the continent) [Lipinskyy et al., 2003].

One of the features of typical mid-latitude continental seasonal variation of temperature is the minimum in January and the maximum in July (annual range of temperature *A*). On average across the territory of Ukraine, the difference in annual temperature range (January and July) from 1900 to 2021 fluctuated within about 23—26 °C, while the amplitude of the seasonal temperature is 12.8±1.1 °C (see above).

To evaluate the continentality of the climate, the Johansson-Ringleb indices (K_{J-R}) [Johansson, 1931] were employed:

$$K_{J-R} = 0.6\left(1.6\frac{A_*}{\sin\varphi} - 14\right) - D + 36\,, \quad (3)$$

(for the marine climate — $0 \le K_{J-R} < 40$, continental — $40 \le K_{J-R} < 70$, strongly continental — $70 \le K_{J-R} < 100$).

Here φ is geographic latitude (in degrees), *A* is annual temperature amplitude (to be precise, the annual range of temperature (January—July)), and *D* is the difference between the average values of the autumn (September—November) and spring (March—May) temperatures.

The results of calculations of Johansson-Ringleb (K_{J-R}) continentality indices by (3) for 45 meteorological stations in Ukraine showed that K_{J-R}=59.3±3.7 from 1900 to 2021 and K_{J-R}=59.0±3.4 from 1991 to 2020. The analysis of the continentality indices for the 20th century and the beginning of the 21st century showed a general tendency to decrease by 0.4 % per 100 years (related to more warming in the cold period of the year), whereas from 1991 to 2020, the increasing tendency revealed K_{J-R} by 6.4 % per 10 years as the temperature began to increase significantly in the warm period of the year.

The variations of the continentality indices in Ukraine from 1900 to 2021 are shown in Fig. 15. Some cycles are observed in their century course: minimum values in 1902, 1918, 1948, 1952, 1984, and 2020 years, and maximum values in 1947, 1950, 1954, 1963, 1972 and 1987 years.

The spatio-temporal distribution of continentality indices K_{J-R} and their trends in Ukraine for the periods from 1900 to 2021 are shown in Fig. 16.

As we can see from Fig. 16, *b*, trends of continentality indices K_{J-R} have negative values over most of Ukraine. That is further confirmation of the fact that one of the modern regional features of climate change is the spatio-temporal transformation of the amplitude of the seasonal temperature variation,

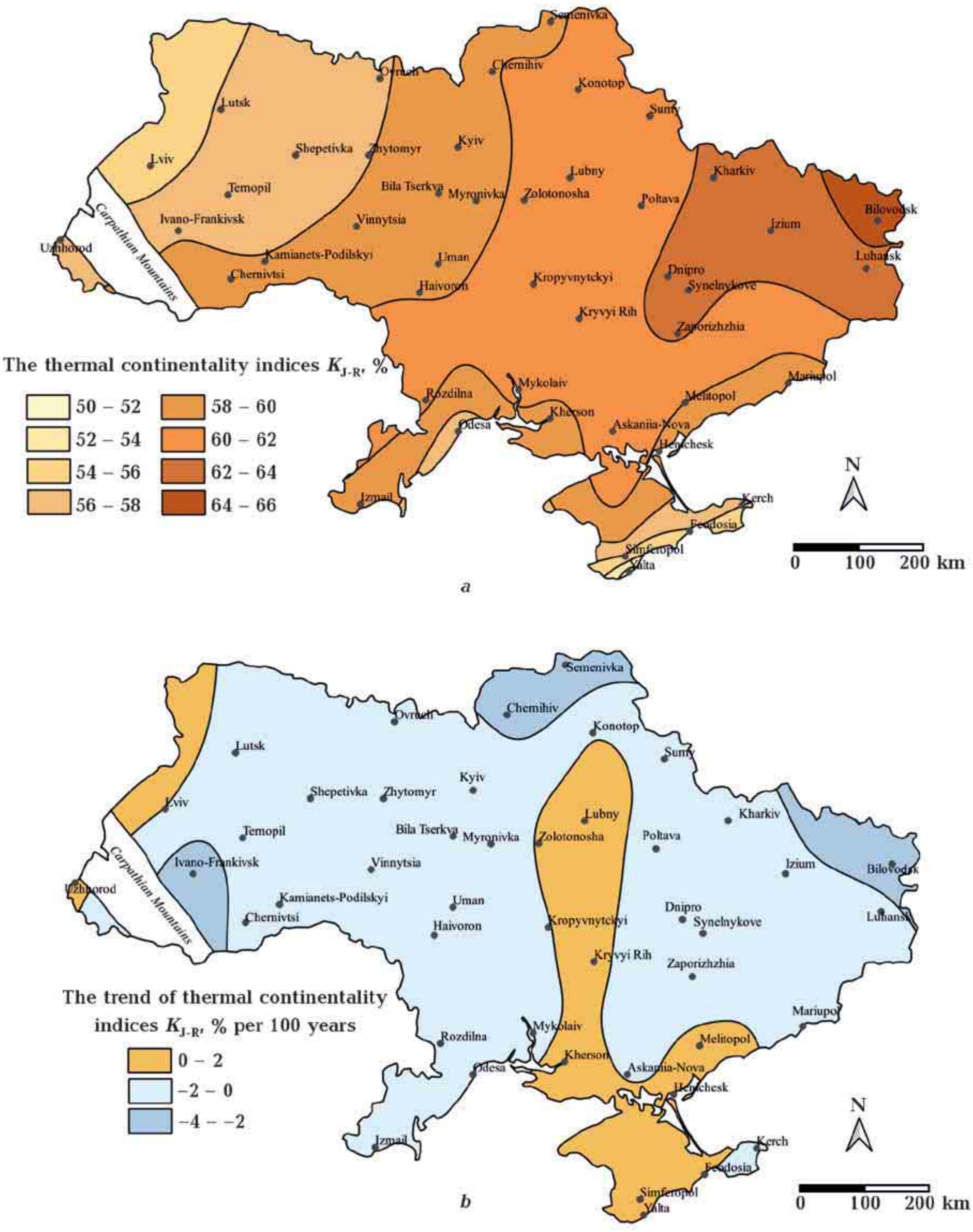


Fig. 16. The spatio-temporal distribution of continentality indices K_{J-R} (*a*) and their trends (*b*) in Ukraine for the periods from 1900 to 2021.

due to sufficiently significant warming, which led to a decrease in the continentalization [Lee et al., 2021], including in Ukraine (the decontinentalization effect) [Voloshchuk,

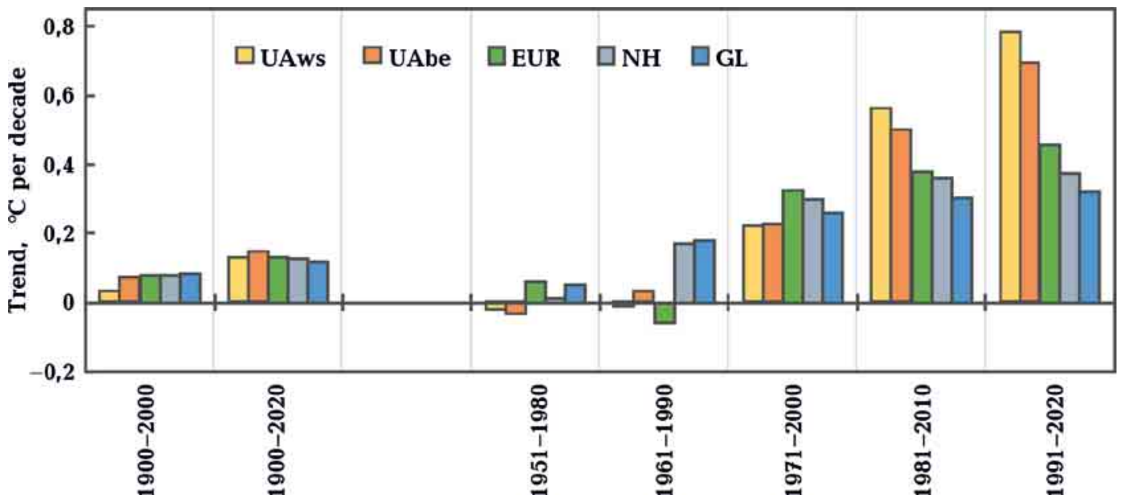


Fig. 17. Comparison of tendency changes of average annual surface air temperature Global land (GL), Northern Hemisphere (NH), Europe (EUR), and Ukraine (weather dataset UA_{be} and UA_{ws}) from 1900 to 2020 for different periods.

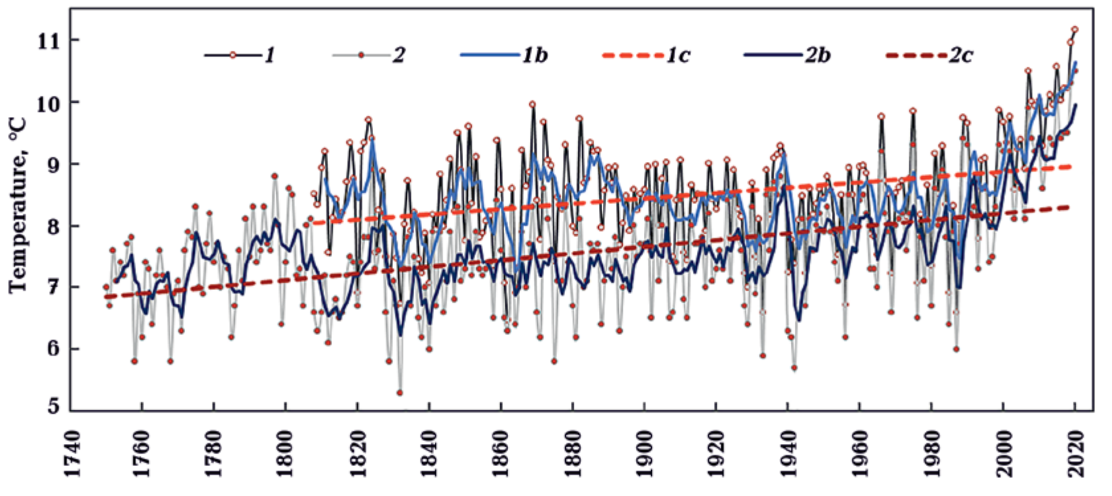


Fig. 18. Long-term average annual surface air temperature (*1* — UA_{ws} dataset; *2* — UA_{be} dataset; *1a*, *2a* — five-year moving averages; *1b*, *2b* — linear trends, respectively) in Ukraine from 1750 to 2020.

Boychenko, 2003; Boychenko et al., 2018]. Truly, such periods of fluctuations in the continentality indices and the amplitude of the seasonal temperature variation were observed throughout the 20th century and at the beginning of the 21st century in other regions [Ciaranek, 2014; Vilček et al., 2016; Szabó-Takács et al., 2015].

Discussion. Changes in average annual surface air temperature from global to regional scales. Climate change warming has manifested divergently across continents and regions and the warming trend has become more pronounced since the 1970s [Lee et al., 2021; Baldos et al., 2023; IPCC, 2023]. The Northern Hemisphere generally experiences higher warming rates than the Southern Hemisphere, while Europe and Ukraine exhibit more high-temperature change rates, displaying temperature change rates that can differ by as much as two times as observed. This suggests that regional warming trends depend on latitude, other geographical conditions, and internal variability [Olonscheck et al., 2021].

We compared the tendency of average annual surface air temperature changes for Global land, the Northern Hemisphere, Europe, and Ukraine based on the Berkeley Earth temperature datasets. For Ukraine in

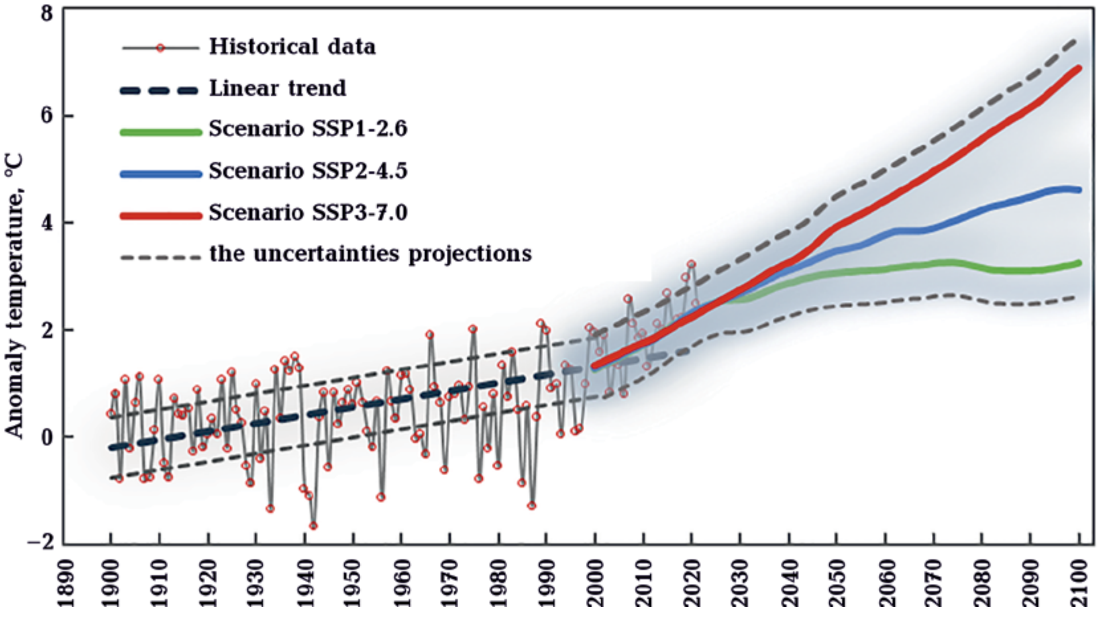


Fig. 19. The annual average surface temperature changes relative to a pre-industrial baseline in the late 19th century in Ukraine (historical data) and the three scenarios of changes (SSP1-2.6, SSP2-4.5, and SSP3-7.0), based on greenhouse emissions scenarios by 2100 (the uncertainties associated with projections). Source [Berkeley …, 2023].

particular, two empirical time series were used for analyses (UA_{be} and UA_{ws}). UA_{be} is the Berkeley dataset, and UA_{ws} is the long-term average annual surface temperature dataset, encompassing 45 stations (Fig. 17).

The comparison between the rate of temperature change over the past several 30-year periods reveals that global, continental, and regional warming rates were not constant throughout the past century. Unlike the recent 30-year periods (1981—2010 and 1991—2020), earlier 30-year periods (1951—1989 and 1961—1991) exhibit distinctively opposite temperature changes on both global and regional scales. From 1990 to 2020, Ukraine was one of the regions in Europe experiencing one of the highest rates of climate change.

The later 30-year period (1991—2020) had stronger and more significant warming trends than the earlier 30-year periods in most regions of the world. Thus, warming has been accelerating in the past decades both globally and regionally.

To analyze long-term climate changes in Ukraine, two long-term temperature series UA_{be} (from 1750 to 2020) and UA_{ws} (from 1808 to 2020) were used (Fig. 18). These series have certain differences associated with weather stations' selection and observation periods. It is worth noting that the time series UA_{be} represents an interpolation based on European weather station data from 1750 to 1800, an interpolation considering early meteorological observations in Ukraine from 1800 to 1900, and an interpolation of modern systematic meteorological observations for 1900—2020 (however, there are data gaps in the time series).

Scenarios of warming in Ukraine. Climate change scenarios are crucial for assessing the consequences of different policy choices and actions related to climate change mitigation and adaptation [IPCC, 2023]. They provide a range of possible futures based on varying levels of greenhouse gas emissions and global temperature increases. In response to global warming, land areas are generally expected to warm faster than ocean areas. This is due to differences in heat capacity and other factors. As a result, national average temperature time series are likely to show more warming than the corresponding global average within the same scenario. Each model scenario comes with a level of uncertainty regarding the future warming response to a given emissions trajectory. Climate models are complex and involve many variables, making it difficult to predict future temperatures [Lee et al., 2021].

The IPCC AR5 featured four RCP (Representative Concentration Pathway) scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) that explored different possible future greenhouse gas emissions trajectories [Lee et al., 2021]. These scenarios represent a range of radiative forcing levels by the year 2100, with RCP2.6 being a low emissions scenario and RCP8.5 representing a high emissions scenario. In CMIP6 (the sixth phase of the Coupled Model Intercomparison Project), these scenarios were updated and renamed as Shared Socioeconomic Pathways (SSPs) [Riahi et al., 2017; Meinshausen et al., 2020]. The new versions of these scenarios are SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. Importantly, these SSPs aim to achieve similar radiative forcing levels by 2100 as their predecessors in AR5. For example, SSP1-2.6 corresponds to a lowemissions pathway similar to RCP2.6, while SSP5-8.5 represents a high-emissions pathway similar to RCP8.5.

The SSPs consider not only greenhouse gas concentrations but also socioeconomic and policy factors that influence emissions pathways. SSP1 is the scenario referred to as *Sustainability — Taking the Green Road (Low challenges to mitigation and adaptation).* It envisions a future characterized by a gradual and widespread shift towards sustainability and inclusive development. SSP2, referred to as *Middle of the Road (Medium challenges to mitigation and adaptation)*, envisions a future where social, economic, and technological trends largely continue along the historical patterns. There are some positive developments, such as reduced resource and energy use intensity and moderate population growth. Still, there are also persistent issues, including income inequality and slow progress towards sustainable development. SSP3 is the scenario referred to as *Regional Rivalry — A Rocky Road (High challenges to mitigation and adaptation*). It posits a future with significant challenges to mitigation and adaptation efforts in the face of various geopolitical and socioeconomic factors. It highlights the potential risks associated with a lack of international collaboration and the consequences of prioritizing security and nationalism over sustainability and global development. This holistic approach helps to provide a clearer picture of the range of possible futures based on a combination of emissions and societal developments.

To create a national average temperature time series for future projections, model data are used to estimate how temperatures will change in specific regions. These data are then rescaled to match historical temperature observations from the same regions [Krakovska et al., 2018]. This process helps to ensure that the model projections align with observed data as closely as possible. The historical temperature data for scenarios were received from the Berkeley Earth source (http://www.berkeleyearth.org).

The scenarios of annual average surface temperature change relative to a pre-industrial baseline in the late 19th century until the end of the 21st century (SSP1, SSP2, and SSP3) in Ukraine are presented in Fig. 19:

- **SSP1-2.6**. Under this scenario by 2100, average global warming is expected to reach approximately 1.8°C above the pre-industrial baseline. This scenario assumes lower greenhouse gas emissions and aims for global net zero CO_2 emissions by around 2050;
- **SSP2-4.5**. This scenario projects an average global warming by the end of this century rise of 2.7 °C. It represents a situation where modern CO_2 emissions levels remain relatively consistent through 2050 before gradually declining;
- **SSP3-7.0**. In this high-emissions scenario, average global temperatures are expected to increase in 2100 by approximately 3.6 °C above the pre-industrial baseline. It assumes that emissions continue to rise.

The **SSP2-4.5** scenario is seen as somewhat representative of the current trajectory of average global temperature if emissions are not significantly curtailed.

Conclusions. We analyzed early (since 1808) historical meteorological observations of air surface temperature on 11 meteostations on the territory of Ukraine. However, since a larger number of stations have time series of temperature starting in 1821—1825, for more reliable estimates of the linear trend, the period 1824—2021 is required. The trend is 0.78 °C per 100 years for this period. The temperature in Ukraine exhibited an increase of 1.31±0.42 °C per 100 years in 1900—2021. Climate change has accelerated significantly since the second half of the 20th century. Over the last 30 years, a more pronounced increase in annual surface air temperature, by 0.79±0.08 °C per decade, was observed.

Changes in the temperature regime exhibit spatio-temporal patterns. In most parts of Ukraine in 1900—2021, a temperature increase is within 1.5—2.0 °C per 100 years. Simultaneously, some parts of northern, northwestern, and eastern regions, as well as the Vinnytska and Zaporizhzhska oblasts, are characterized by more intense warming, reaching 2.0—2.5 °C per 100 years, 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 per 100 years.

Temperature anomalies from 1900 to 2021 indicate the lowest annual averages occurred in 1933, 1956, 1976, 1985, and 1987 (ΔT=–0.68±0.54), while the highest annual averages were observed in 2007, 2015, 2019, and 2020 (ΔT=0.74±0.63). In the recent decade, there has been a significant increase in temperature in Ukraine, as well as globally. Against the backdrop of climate change, noticeable patterns in temperature variations across seasons have come to light. Between 1900 and 2021, the average monthly air temperature in Ukraine increased substantially in colder months (from October to March), ranging from 0.7 to 2.0 °C per century. Simultaneously, warmer months (from April to September) saw an elevation ranging from 1.0 to 1.9 °C per century. In the 1991—2020 norm, an overall warming trend of 0.5—1.3 °C per decade was observed throughout the year. Note, that January showed a slight decrease in the warming rate, with a trend value of –0.1 °C per decade.

Analysis of the temperature amplitude (A) over the 20th century and the early 21st century revealed a general tendency of decreasing its values by –0.5 °C per 100 years, primarily due to warming in the colder months. However, from 1991 to 2020, there was an increasing trend in A by –0.001 °C per decade, attributed to a significant temperature rise during the warmer months.

A contemporary regional aspect of climate change involves the reduction of climate continentalization. Based on the analysis of the continentality indices of Johansson-Ringleb in Ukraine, a tendency to decrease continentality indicators (by 0.4 % in 100 years) was established. However, from 1991 to 2020, a contrasting pattern emerged, with an increase in indices by 6.4 % per decade.

Comparing the warming rates of different periods, it is evident that the later 30-year period (1991—2020) exhibited stronger and more significant warming trends than the earlier 30-year periods of the century in most regions of the world. The three scenarios of annual average surface temperature changes in Ukraine (SSP1-2.6, SSP2-4.5, and SSP3-7.0) relative to pre-industrial levels in the late 19th century, based on greenhouse emissions scenarios by 2100, are discussed.

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Столітній аналіз зміни приземної температури повітря на території України

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Проаналізовано ранні історичні метеорологічні спостереження за приземною температурою повітря, які були розпочаті з 1808 р. на 11 метеостанціях, розташованих на території України. Більша кількість станцій має часові ряди температури починаючи з 1821—1825 р., для більш достовірних оцінок лінійного тренду розрахунок був проведений з 1824 по 2021 р. Тренд становить 0,78 °С/100 років для того періоду.

За аналізом метеорологічних даних середньорічна температура повітря на території України в період з 1900 по 2021 р. становила 8,6±0,9 °С. Однак для більш нового періоду з 1991 по 2020 р. вона зросла до 9,5±0,9 °С. Температурний тренд становить 1,31±0,42 °С/100 років для цього періоду. За останні 30 років спостерігається більш виражений тренд до 0,79±0,08 °С/10 років.

Зміни в режимі температури мають просторово-часові особливості в межах території України. На більший частині території країни зафіксовано зростання температури в межах 1,5—2,0 °С за період 1900—2021 рр. Водночас у північних, північно-західних і східних регіонах, а також Вінницький і Запорізькій областях відбулося більш інтенсивне потепління — 2,0—2,5 °С, на відміну від південно-західних, південних регіонів і Передкарпаття, де тренд становить 1,0—1,5 °С.

Аномалії температури з 1900 по 2021 р. засвідчують, що найхолодніші середньорічні значення були зафіксовані у 1933, 1956, 1976, 1985 і 1987 р., тоді як найтепліші — у 2007, 2015, 2019 і 2020 рр.

За період 1900—2021 рр. середньомісячна температура повітря в Україні значно зросла в холодні місяці (від жовтня до березня), варіюючи від 0,7 до 2,0 °С/100 років, тоді як у теплі місяці (від квітня до вересня) вона виявилася вищою на 1,0—1,9 °С/100 років. За нормою 1991—2020 рр. спостерігався загальний тренд потепління в межах 0,5—1,3 °С/10 років. Слід зазначити, що січень показав слабке зменшення темпів потепління — на –0,1 °С/10 років.

Індикатором сезонності кліматичних умов є амплітуда температури повітря на поверхні. В Україні середня амплітуда становила 12,7±1,1 °С з 1900 по 2021 р. і 12,5±0,8 °С з 1991 по 2020 р. Аналіз амплітуди температури виявив загальну тенденцію зменшення значень тренду *A* на –0,5 °С/100 років переважно через потепління в холодні місяці. Однак з 1991 по 2020 р. спостерігається зростання тренду *A* на –0,001 °С/10 років, що пов'язане з великим підвищенням температури протягом теплих місяців.

На підставі аналізу індексів континентальності Johansson-Ringleb в Україні було визначено значення індексів як 59,3±3,7 за період 1900—2021 рр. і 59,0±3,4 за період 1991—2020 рр. Загальна тенденція вказує на зменшення індексів на 0,4 %/100 років. Проте з 1991 по 2020 р. виявлено протилежну тенденцію, яка показує зростання індексів на 6,4 %/10 років.

Наведено три сценарії змін середньорічної температури в Україні (SSP1-2.6, SSP2-4.5 і SSP3-7.0) стосовно доіндустріальних рівнів з кінця XIX ст. на основі сценаріїв викидів парникових газів до 2100 р.

Ключові слова: середньорічна та середньомісячна приземна температура повітря, амплітуда температури, індекси континентальності, аномалії температури, сценарії зміни температури.