УДК 551.51 DOI: https://doi.org/10.24028/gj.v45i2.278328

*In memory of Professor Volodymyr Voloshchuk*

# Semi-empirical model of the spatiotemporal surface temperature distribution on the plain part of Ukraine

***S. Boychenko[1], N. Maidanovych[2], 2023***

[1]S.I. Subbotin Institute of Geophysics of the National Academy of Sciencesof Ukraine, Kyiv, Ukraine
[2]Leonid Pogorilyy UkrNDIPVT, Doslidnyts'ke, Ukraine
Received 2 February 2023

The spatial variation of temperature is found to depend linearly on climate continentality, morphology of the relief, the position of the site with respect to seas, in addition to the usual elevation, latitude and longitude predictors. There are other factors that can have an additional significant influence: big bodies of water, terrain attributes relief, atmospheric factors (local circulation), configuration and aspect of coasts and vegetation. Therefore, these multifactorial influences form the climatic field of temperature.

In this study, the regional semi—empirical model of the spatiotemporal distribution of the average annual and monthly temperature for the plain part of Ukraine on the basis of the methodology for assessing the influence of height above sea level and geographic coordinates is proposed. Based on the method for determining the altitudinal, latitudinal, and longitudinal gradients of meteorological parameters, we calculated these gradients for annual and monthly air surface temperature for the periods 1961—1990 and 1991—2020.

Thus, on the plain part of Ukraine, the annual surface air temperature decreases by an average on 0.60—0.63 °C with a shift of 100 m height above sea level, on 0.51—0.55 °C with a shift of one latitude degree to the north, on 0.067—0.071 °C with a shift of one longitude degree to the east. Also, the variations of these annual mean temperature gradients from year to year are characteristic.

The seasonal variation of gradients has a pronounced non—monotonic character: highest values of altitudinal gradientare typical for July—August (from –0.63 to –0.73 °C per 100 m), and the lowest values — for April—May (from –0.45 to –0.55 °C per 100 m); highest values of latitudinal gradient are typical for August—September (from –0.60 to –0.70 °C per 1 °N), and the lowest values — for April—May (from –0.20 to –0.35 °C per 1° N); the longitudinal gradients have positive values in June—August (0.074—0.128 °C per 1° E), and negative values in November—March (from –0.228 to –0.154 °C per 1° E).

We found that the altitudinal and latitudinal gradients of temperature have the most spatiotemporal variability and the longitudinal gradient has the smallest one. Greatest variabilities of temperature gradient values are typical for February—March and July—September, and the least variability — for April—May.

The analysis of the dynamics of gradient changes in the period 1991—2020 compared to the period 1961—1991 showed the following: the altitudinal gradientvalues increased by 8—13 % in January and March—May; the latitudinal gradient values increased by ~30 % in December—February and decreased by ~20 % in May—August.

The proposed semi—empirical model contains a coefficient that takes into account influence of additional effects associated with pronounced orographic and other terrain

Citation: *Boychenko, S., & Maidanovych, N.* (2023). Semi-empirical model of the spatiotemporal surface temperature distribution on the plain part of Ukraine. *Geofizicheskiy Zhurnal*, *45*(2), 63—76. https://doi.org/10.24028/gj.v45i2.278328.

features. This study presents the numerical values of this coefficient for some specific microclimate regions of the plain part of Ukraine.

The model estimates of thirty—year monthly mean temperature in Ukraine for the periods 1961—1990 and 1991—2020 was calculated. A comparison of the model estimates of of the average annual and monthly temperature for 72 meteostations in Ukraine with their actual values showed a statistically significant correlation (the reliability of the linear approximation is 0.89—0.98). Thus, the presented design of the semi-empirical model makes it possible to quite well restore the annual and monthly temperature on the territory of Ukraine.

**Key words:** altitudinal, latitudinal, and longitudinal gradients; the average annual and monthly temperature; climatic norm; semi-empirical model.

**Introduction**. The spatial variation of the within-year pattern temperatures is found to depend linearly on climate continentality, relief morphology, and position of the site with respect to seas, in addition to the usual elevation, latitude, and longitude predictors [de Castro et al., 2007; Habit et al., 2022]. Also,other factors can have a significant additional influence, including big water bodies, terrain relief attributes, atmospheric factors (local atmospheric circulation), and configuration and aspects of coasts and vegetation [Daly et al., 2002; Serbin, Kucharik, 2009]. Together, these multifactorial influences form the climatic field of temperature.

The effect of altitudinal zonation is most pronounced in mountainous areas and regions with orographic heterogeneity [Johansson, 2000; Daly et al., 2002; Lookingbill, Urban, 2003; Claps et al., 2008]. While the reaction of meteorological conditions to terrain height changes is less noticeable in the plain land regions (up to altitudes of 350—400 m above sea level), it can still form a certain microclimate.

The global value of the vertical temperature gradient in the troposphere is –0.65±0.06 °C/100 m (that is, the temperature decreases with height by 0.65 °C with every 100 m) [Oliver, 2005]). In plain regions, the response of meteorological parameters to the height of the area above sea level is less noticeable (up to 350—400 m). However, it can still form certain microclimatic conditions and cannot be neglected. Microscale features of the weather station's location or the region generate a specific «microclimatic noise» and transfer their climatic fields to the rank of stochastic [Boychenko, Voloshchuk, 2007; Tutmez et al., 2012]. Analytical representation of climatic fields has an important advantage — it naturally takes into account the spatial and temporal connectivity of climatic parameters and thereby allows automatic filtering of random «outliers» in the data array [Ninyerola et al., 2000; Boychenko, Serdyuchenko, 2005; Claps et al., 2008].

The seasonal variability of temperature, namely the amplitude of the seasonal course, depends on the latitude. One of the climatic indicators that incorporate the influence of latitude is the index of continentality [de Castro et al., 2007; Boychenko et al., 2018]. Note that the influence of longitude on the temperature distribution is insignificant and thus often neglected.

The basic principles of the methodology of assessing the dependence of meteoparameters (surface air temperature and precipitations) on the area height above sea level and geographical coordinates in Ukraine were researched by Voloshchuk and others [Voloshchuk, Boychenko, 2003; Boychenko, Serdyuchenko, 2005; Boychenko, Voloshchuk, 2007; Boychenko, 2008]. This type of methodology is used to homogenize the climatic fields of surface temperature and precipitation [Boychenko, Serdyuchenko, 2005; Vrac, 2007; Mcroberts, Nielsen-Gammon, 2011].

**Method and Data**. In this study, we used time series of average monthly air temperature values ($T$, °C per month) for 72 meteostations (a set of $\Omega_{72}$) almost uniformly spread on the territory of Ukraine (with height above sea level to 350 m), for the periods 1961—1990 [The Climate…, 2005] and 1991—2020 [CGO, 2021].

The software packages MS Excel and XLSTAT were used for the statistical analysis and graphical design.

*Study Region*. Ukraine is situated in the central part of Eastern Europe between 44.34 and 52.33° N and 22.08 and 41.25° E. Most of the country is located southwest of the Eastern European plain, with elevations generally below 350 m. There are the Ukrainian Carpathian Mountains in the west and the Crimean Mountains in the south. The absolute height of the territory of Ukraine ranges from –5 m (water level in Kuialnyk Estuary) to 2061 m (Goverla Mountain). The coasts of the Black and Azov Seas in Ukraine are mainly flat, except for the Crimean Mountains [Marynych, Stetsenko, 2006].

The climate of Ukraine is mostly temperate continental and subtropical Mediterranean type on the southern portions of the Crimean Peninsula. The Transcarpathian Lowland has specific to mild climate (warm low-snow winters and rainy summers) [Lipinskyy et al., 2003]. According to the analysis of meteorological data, the average annual temperatures were from 7 to 13 °C in the plain part of Ukraine in 1900—2020. The average monthly temperatures in winter vary from –2 to –10 °C, and in summer, from 17 to 25 °C.

The territory of Ukraine has complex climatic and orographic features, and therefore several proxy regions are distinguished. These regions and meteorological stations used for modelling are shown in Fig. 1. This study excluded the Carpathian Mountains and the Crimean Peninsula.

**Method for determining the altitudinal, latitudinal, and longitudinal gradients of meteorological parameters.** Altitudinal ($G_h$), latitudinal ($G_\varphi$), and longitudinal ($G_\lambda$) gradients of average monthly temperature for the set of $\Omega_{72}$ were estimated using the least squares method [Voloshchuk, Boychenko, 2003; Boychenko, Serdyuchenko, 2005; Boychenko, Voloshchuk, 2007; Boychenko, 2008]. According to this, it is assumed that the parameters of the selected function take such values $\{T_m\}$ that the average squared deviations of the empirical data for $\{T\}$ from those estimated by the selected function would be the smallest.

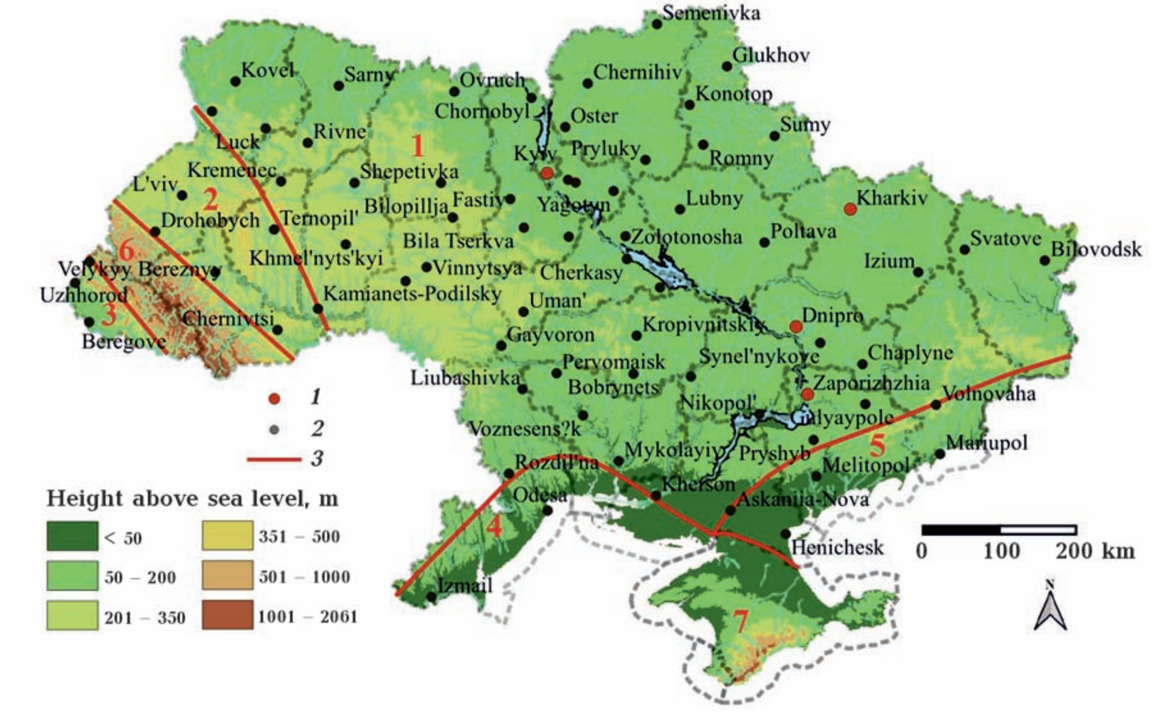


Fig. 1. Climatic subzones and location of meteorological stations of Ukraine used in this study (Region 1: the plain part of Ukraine; Region 2: Foothill area (with altitude up to 350—400 m); Regi on 3: Transcarpathian Lowland; Region 4: the coastal regions of the Black Sea; Region 5: Sivash and Azov regions; Region 6: Carpathian Mountains; Region 7: Crimean Peninsula; also meteostations are grey points, мegapolises are red points).

Gradients $G_h$, $G_\varphi$, and $G_\lambda$, which characterize the effect of landscape and physiographic location, may be a weak signal against a high-noise background. The altitudinal gradient $G_h$ of the meteorological parameter $\{T\}$ was calculated by the following relations (and $G_\varphi$ and $G_\lambda$ according to a similar scheme):

$$G_h = \frac{D_h}{D_0},\ x_1 = h_k - \langle h \rangle,$$

$$x_2 = \varphi_k - \langle \varphi \rangle,\ x_3 = \lambda_k - \langle \lambda \rangle, \qquad (1)$$

$$G_h = \frac{D_h}{D_0},\ D_h = \begin{vmatrix} \langle x_1 T \rangle & \langle x_1 x_2 \rangle & \langle x_1 x_3 \rangle \\ \langle x_2 T \rangle & \langle x_2^2 \rangle & \langle x_2 x_3 \rangle \\ \langle x_3 T \rangle & \langle x_2 x_3 \rangle & \langle x_3^2 \rangle \end{vmatrix},$$

$$D_0 = \begin{vmatrix} \langle x_1^2 \rangle & \langle x_1 x_2 \rangle & \langle x_1 x_3 \rangle \\ \langle x_1 x_2 \rangle & \langle x_2^2 \rangle & \langle x_2 x_3 \rangle \\ \langle x_1 x_3 \rangle & \langle x_2 x_3 \rangle & \langle x_3^2 \rangle \end{vmatrix},$$

Let us expand $D_h$ in terms of the algebraic complements of the column of its determinant, namely:

$$D_h = \left\langle \left(T - \langle T \rangle\right)\left[x_1 D_1 - x_2 D_2 + x_3 D_3\right] \right\rangle,$$

$$D_1 = \begin{vmatrix} \langle x_2^2 \rangle & \langle x_2 x_3 \rangle \\ \langle x_2 x_3 \rangle & \langle x_3^2 \rangle \end{vmatrix},\ D_2 = \begin{vmatrix} \langle x_1 x_2 \rangle & \langle x_1 x_3 \rangle \\ \langle x_2 x_3 \rangle & \langle x_3^2 \rangle \end{vmatrix},$$

$$D_3 = \begin{vmatrix} \langle x_1 x_2 \rangle & \langle x_1 x_3 \rangle \\ \langle x_2^2 \rangle & \langle x_2 x_3 \rangle \end{vmatrix}, \qquad (2)$$

where $h_k$, $\varphi_k$ and $\lambda_k$ are elevation, latitude, and longitude for the *k–th* meteostation, $k = \overline{1.72}$; $\langle h \rangle$, $\langle \varphi \rangle$ and $\langle \lambda \rangle$ are the average values of the elevation, latitude, and longitude for all considered meteostations.

It is assumed that «microclimatic noise» for this network of meteostations is statistically independent. Then, using relations (1), the variance of gradient $G_h$ can be expressed in terms of the variance $\{T\}$, and $dsp\{T\}$ denotes the variance of a random variable. Since we are identifying and evaluating an «extremely weak signal against a background of very large noise», then in order to justify the statistical significance of the result obtained based on the relation (2), the root-mean-square error (s) is necessary:

$$s = \chi\sqrt{dsp\{G_h\}}, \qquad (3)$$

where $n$ is the number of considered meteostations; $dsp\{T\}$ is the dispersion of $\{T\}$ values.

**Results.** ***The effect of elevation and physiographic location on surface air temperature values.*** By approximations (1) and (2), the altitudinal, latitudinal, and longitudinal gradients of surface air temperature were calculated, namely their average yearly values, dispersion, androot-mean-square error by approximations (3).

Annual and seasonal variations of the altitudinal, latitudinal, and longitudinal temperature gradients for the two climatic norm periods 1961—1991 ($T_1$) and 1991—2020 ($T_2$) are as follows.

*Altitudinal gradient.* By the calculations, the annual values of the altitudinal gradients of temperature (a set of $\Omega_{72}$ stations) are $G_h\{T_1\}$=–0.63±0.24 and $G_h\{T_2\}$=–0.60±0.22 °C

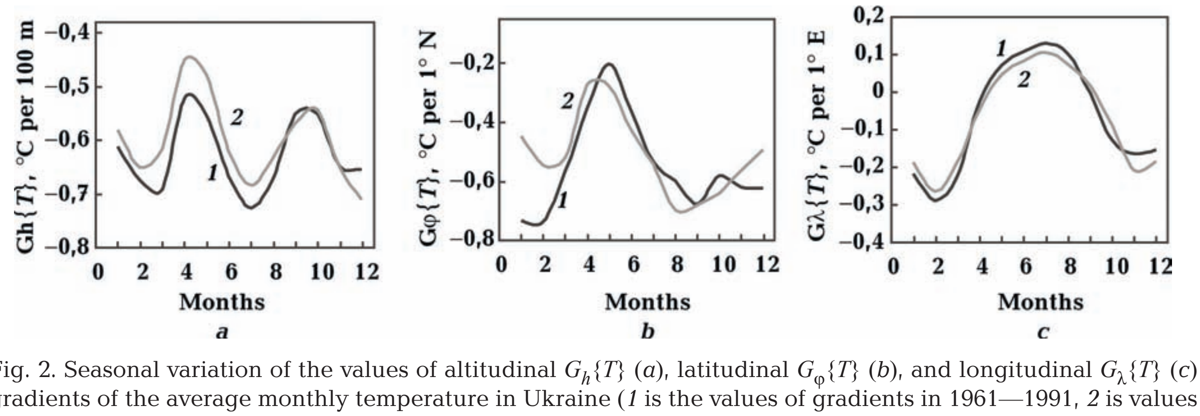


Fig. 2. Seasonal variation of the values of altitudinal $G_h\{T\}$ (*a*), latitudinal $G_\varphi\{T\}$ (*b*), and longitudinal $G_\lambda\{T\}$ (*c*) gradients of the average monthly temperature in Ukraine (*1* is the values of gradients in 1961—1991, *2* is values of gradients in 1991—2020).

per 100 m. The seasonal variation of gradients has a pronounced non-monotonic character (Fig. 2, *a*). The highest values of $G_h\{T\}$ are typical for July—August (from –0.63 to –0.73 °C per 100 m) and the lowest for April—May (from –0.45 to –0.55 °C per 100 m). Thus, every 100 m upwards, the temperature decreases on average by 0.60—0.63 °C. However, in January and March—May, for the period 1991—2020, it increased by 8—13 %.

*Latitudinal gradient.* The annual values of the region's latitudinal gradients of temperature are $G_\varphi\{T_1\}$=–0.55±0.11 and $G_\varphi\{T_2\}$= =–0.51±0.10 °C per 1° latitude, respectively. The $G_\varphi\{T\}$ values have a pronounced seasonal variation (Fig. 2, *b*). For example, the gradients $G_\varphi\{T\}$ take on maximum values from –0.60 to –0.70 °C per 1° N in August—September and minimum values from –0.20 to –0.35 °C per 1 °N in April—May. Thus, for every degree to the north, the temperature decreases on average by 0.51—0.55 °C. In December—February, it increased by ~30 %, and in May—August decreased by ~20 % in 1991—2020 compared to the 1961—1991 period.

*Longitudinal gradient.* The annual values of the longitudinal gradients of average monthly temperature are $G_\lambda\{T_1\}$=–0.067±0.043 and $G_\lambda\{T_2\}$=–0.071±0.039 °C per 1° longitude. The seasonal course of the $G_\lambda\{T\}$ is pronounced (Fig. 2, *c*). The longitudinal gradient has positive values in the warm season (June—August), in the range of 0.074—0.128 °C per 1° E, and negative values in the cold season (November—March), in the range from –0.228 to –0.154 °C per 1° E. Thus, for every degree to the East, the surface air temperature decreases on an average by 0.067—0.071 °C.

**Table 1. Average monthly and annual values of altitudinal ($G_h$), latitudinal ($G_\varphi$) and longitudinal ($G_\lambda$) surface temperature gradients (climatic norms) and their root-mean-square errors (*s*) in Ukraine in 1961—1991 and 1991—2020**

| Parameters | Months | | | | | | | | | | | | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | |
| 1961—1990 | | | | | | | | | | | | | |
| $G_h\{T\}$, °C per 100 m | –0.61 | –0.67 | –0.69 | –0.52 | –0.55 | –0.67 | –0.73 | –0.67 | –0.55 | –0.55 | –0.65 | –0.66 | –0.63 |
| *s*, °C per 100 m | 0.31 | 0.33 | 0.27 | 0.19 | 0.20 | 0.27 | 0.33 | 0.33 | 0.29 | 0.24 | 0.26 | 0.27 | 0.24 |
| $G_\varphi\{T\}$, °C per 1° N | –0.73 | –0.74 | –0.57 | –0.35 | –0.20 | –0.36 | –0.54 | –0.60 | –0.68 | –0.58 | –0.62 | –0.62 | –0.55 |
| *s*, °C per 1° N | 0.14 | 0.15 | 0.12 | 0.09 | 0.09 | 0.12 | 0.15 | 0.15 | 0.13 | 0.11 | 0.12 | 0.12 | 0.11 |
| $G_\lambda\{T\}$, °C per 1° E | –0.219 | –0.288 | –0.225 | –0.025 | 0.069 | 0.106 | 0.128 | 0.101 | –0.005 | –0.129 | –0.165 | –0.154 | –0.067 |
| *s*, °C per 1° E | 0.055 | 0.059 | 0.048 | 0.034 | 0.035 | 0.048 | 0.059 | 0.059 | 0.051 | 0.043 | 0.047 | 0.048 | 0.043 |
| 1991—2020 | | | | | | | | | | | | | |
| $G_h\{T\}$, °C per 100 m | –0.58 | –0.65 | –0.62 | –0.45 | –0.48 | –0.62 | –0.68 | –0.63 | –0.57 | –0.54 | –0.65 | –0.71 | –0.60 |
| *s*, °C per 100 m | 0.22 | 0.27 | 0.24 | 0.15 | 0.19 | 0.26 | 0.32 | 0.34 | 0.30 | 0.26 | 0.26 | 0.24 | 0.22 |
| $G_\varphi\{T\}$, °C per 1° N | –0.45 | –0.55 | –0.52 | –0.28 | –0.28 | –0.43 | –0.54 | –0.70 | –0.68 | –0.64 | –0.57 | –0.50 | –0.51 |
| *s*, °C per 1° N | 0.10 | 0.12 | 0.11 | 0.07 | 0.08 | 0.12 | 0.14 | 0.15 | 0.13 | 0.12 | 0.12 | 0.11 | 0.10 |
| $G_\lambda\{T\}$, °C per 1° E | –0.188 | –0.265 | –0.188 | –0.046 | 0.044 | 0.083 | 0.105 | 0.074 | 0.015 | –0.091 | –0.209 | –0.185 | –0.071 |
| *s*, °C per 1° E | 0.039 | 0.049 | 0.042 | 0.028 | 0.033 | 0.047 | 0.056 | 0.060 | 0.053 | 0.046 | 0.046 | 0.043 | 0.039 |

Seasonal variations of the root-mean-square error for altitudinal $G_h\{T\}$, latitudinal $G_\varphi\{T\}$, and longitudinal $G_\lambda\{T\}$ temperature gradients for both analyzed periods are presented in Table 1. As we can see, the greatest variabilities of temperature gradient values for both periods are typical for February—March and July—September, and the least variability, for April—May.

The altitudinal, latitudinal, and longitudinal gradients of average yearly temperature from year to year in 1991—2020 areas follows:

*Altitudinal gradient.* Per the calculations, the annual values of the altitudinal gradients of temperature from year to year in 1991—2020 are $G_h\{T_{\text{year}}\}$=–0.59±0.07 °C per 100 m. The lowest $G_h\{T_{\text{year}}\}$ values were in 2007, 2015—2018, and 2020 (from –0.40 to –0.49 °C per 100 m) and the highest in 1996 and 2014 (from –0.68 to –0.76 °C per 100 m) (Fig. 3, *a*).

*Latitudinal gradient.* The annual values of latitudinal gradients of temperature from year to year are $G_\varphi\{T_{\text{year}}\}$=–0.50±0.08 °C per 1° N. The lowest values of $G_\varphi\{T_{\text{year}}\}$ were in 1992, 2007, and 2020 (from –0.25 to –0.39 °C per 1° N) and the highest in 1994 and 2013 (from –0.65 to –0.62 °C per 1° N) (Fig. 3, *b*).

*Longitudinal gradient.* The annual values of this region's longitudinal gradients of temperature from yearto year are $G_\lambda\{T_{\text{year}}\}$=–0.07±0.05 °C per 1° E. The lowest values of $G_\lambda\{T_{\text{year}}\}$ were in 1995, 2005, 2010, and 2020 (from –0.02 to 0.04 °C per 1° E), and the highest in 1994 and 2007 (from –0.15 to –0.18 °C per 1° E) (Fig. 3, *c*).

Year-to-year variations of the root-mean-square errors for altitudinal $G_h\{T\}$, latitudinal $G_\varphi\{T\}$, and longitudinal $G_\varphi\{T\}$ gradients in Ukraine in 1991—2020 were calculated by (3) and are shown in Fig. 3.

As we can see, the temperature's altitudinal and latitudinal gradients have the most significant spatiotemporal variability, and the longitudinal gradient has the smallest one. Together these gradients generate the «microclimatic noise» of temperature.

**Semi-empirical model of the spatiotemporal distribution of the average monthly surface air temperature for the flat part of Ukraine in 1991—2020.** An equation for the relationship between experimental data is semi-empirical if its form is determined theoretically and some of the coefficients involved are determined experimentally. At the first approximation, the dependence of a meteorological parameter (in this case, the surface air temperature) on the geographical coordinates and height of the landscape above sea level for the plain part of Ukraine (excluding the Ukrainian Carpathians and the Crimea Peninsula) can be represented as a linear function:

$$T\{\text{mod}(k,m)\} \approx \langle T(m)\rangle + G_h(m)\left(h_k - \langle h\rangle\right) + \\ + G_\varphi(m)\left(\varphi_k - \langle\varphi\rangle\right)\ldots \\ \ldots + G_\lambda(m)\left(\lambda_k - \langle\lambda\rangle\right) + \varepsilon(R) \qquad (4)$$

where $\langle T(m)\rangle$ is the average monthly surface air temperature on the territory for a certain month $m=\overline{1.12}$; $G_h$, $G_\varphi$, and $G_\lambda$ are altitudinal, latitudinal, and longitudinal temperature gradients; $\varepsilon\{R\}$ is coefficient (approximately from –1.5 to 1.5) whose value depends on orography, proximity to the seas, etc.

It is obvious that for flat regions with relatively low altitudes above sea level (to 350 m), at the first approximation, the dependence of

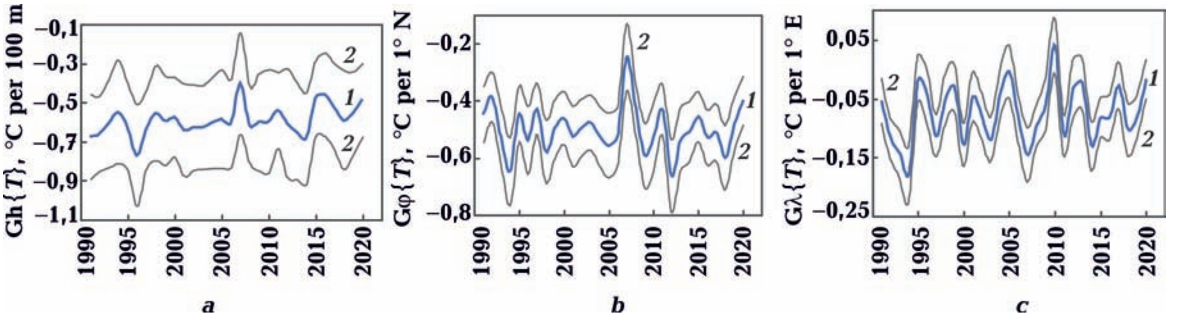


Fig. 3. Time course of the average annual values of altitudinal $G_h\{T\}$ (*a*), latitudinal $G_\varphi\{T\}$ (*b*), and longitudinal $G_\lambda\{T\}$ (*c*) gradients of surface air temperature in Ukraine in 1991—2020 (*1* is gradient, *2* is ±s).

meteoparameters on altitude can be taken as linear.

In plain regions with uniform low terrain, differences between actual and model values are negligible. However, there are also effects imposed by pronounced orographic and other terrain features, such as:

• the effect of mountainous regions with a height above sea level above 350 m, taking into account the exposure of slopes and local winds, for example, the Carpathian and Crimean Mountains;

• windward hydrodynamic effect, when the region is located in front of a mountain range (in terms of tropospheric air mass transfer), such as Transcarpathia;

• leeward hydrodynamic effect (in terms of air mass transfer) when the region is located behind a mountain range, for example, the Foothill area;

• the effect of breeze circulation, for example, the coastal regions of the Black and Azov Seas;

• the effect of a practically «closed-off»

**T a b l e 2. The coefficient ε{*R*} of model (4) of the seasonal temperature variation for climatic norms 1961—1990 and 1991—2020 and annual values over 1991—2020 for some Ukrainian regions**

| Region | Station | Climatic norm 1961—1990 | Climatic norm 1991–2020 | Annual over 1991—2020 |
|---|---|---|---|---|
| Sivash and Azov regions | Askaniia-Nova | from +0.3 to +0.8 (March—June) | from +0.8 to +0.4 (April—June) | — |
| | Henichesk | from +0.6 to +1.0 (March—June) –0.6 (October—January) | from +0.3 to +0.8 (March—June) | — |
| | Volnovaha | –0.4 (February—August) | –0.5 (January—March and July—October) | –0.5 |
| Transcarpathia region | Beregove | from –0.6 to –1.4 (February—September) | from –0.4 to –1.1 (March—October) | –0.5 |
| | Uzhhorod | from –0.5 to –1.3 (February—October) | from –0.3 to –1.0 (March—October) | –0.4 |
| | Velikiy Berezny | –0.4 (February—March) and +0.5 (July—January) | –0.3 (March—April) | — |
| Foothill area with altitude up to 350 m | Kremenec | –0.6 (September—March) | –0.6 (September—March) | –0.4 |
| | Chernivtsi | +0.4 (November—February) | +0.4 (November—January) | — |
| | Drohobych | –0.4 (November—March) and +0.5 (May—June) | –0.4 (December—February) and +0.4 (April—September) | — |
| | Ivano-Frankivs'k | +0.4 (all months) | +0.5 (all months) | +0.5 |
| | Kamianets-Podilsky | +0.4 (July—February) | +0.5 (December—February) | — |
| | L'viv | –0.4 (November—February) | –0.4 (November–February) | — |
| Megacities with «heat island» effect | Dnipro | –0.5 (February—September) | –0.5 (March—October) | –0.4 |
| | Kharkiv | –0.4 (February—October) | –0.5 (April—October) | –0.4 |
| | Kyiv | –0.5 (all months) | –0.6 (all months) | –0.6 |
| | Zaporizhzhia | –0.7 (all months) | –0.7 (all months) | –0.7 |
| Regions close to the Black Sea | Odesa | –0.7 (October—January) and from +0.4 to +1.1 (March—July) | –0.8 (October—January) and from +0.4 to +1.0 (March—June) | — |
| | Izmail | +0.4 (all months) | +0.5 (July—September) | +0.2 |
| | Liubashivka | +0.4 (November—March) | — | — |

climatic region, such as the southern coast of Crimea;

• the effect of specific climatic conditions (the aridest region), such as the Sivash and Azov regions;

• the effect of «heat island» in megacities (Kyiv, Zaporizhzhia, etc.)

For these regions, the coefficient ε{*R*} is introduced in (4), which depends on the effects of the proximity of the region to mountains or

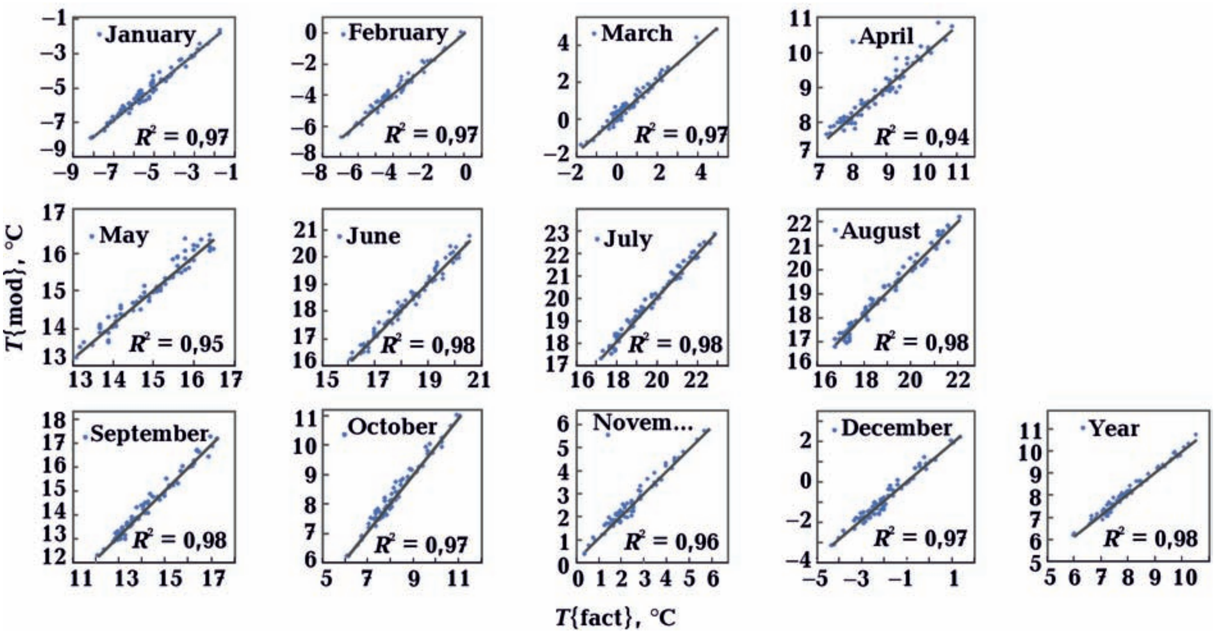


Fig. 4. Comparison of model estimates of climatic norms of average annual and monthly surface temperature values *T*{mod}) with their actual values *T*{fact} in Ukraine for the period 1961—1991 (line is linear regression, *R* is reliability).

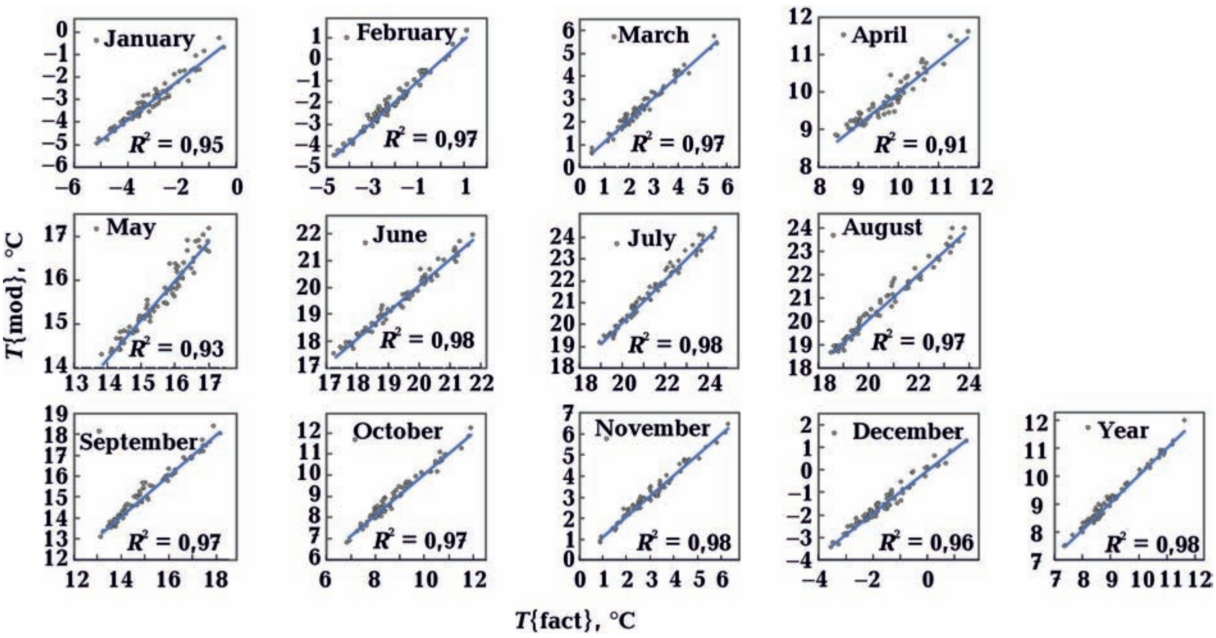


Fig. 5. Comparison of model estimates of climatic normsof average annual and monthly surface temperature values *T*{mod}) with their actual values *T*{fact} in Ukraine for the period 1991—2020 (line is linear regression, *R* is reliability).

seas, as well as on the degree of manifestation of the «heat island» effect, etc. The value of ε{*R*} for some specific microclimate Ukrainian regions in 1961—1990 and 1991—2020 are presented in Table 2. Note that the values of ε{*R*} have a certain similarity for the two periods.

**The model estimates of thirty-year monthly mean temperature in Ukraine in 1961—1990 and 1991—2020**. Based on approximation (4), for each station and each month, the climatic norms of the temperature *T*{mod(*k*,*m*)} were calculated for the set $\Omega_{72}$ (taking into account coefficient ε{*R*}; see Table 2). A comparison of model estimates of climatic norms of the annual and monthly temperature values *T*{mod} with their actual values *T*{fact} for the set $\Omega_{72}$ are shown in Fig. 4 (1961—1991) and Fig. 5 (1991—2020). The reliabilities of the linear approximations ($R^2$) are 0.91—0.98.

**The model estimates of average annual surface temperature in Ukraine in 1991—2020**. The model values of the average annual surface temperature for each station and each year in 1991—2020 were calculated by (1—4). For example, interannual dynamics of average annual temperatures *T*{fact} recorded for Kyiv, Chernihiv, Dnipro, Kharkiv, Kherson, Kropyvnytskyi, Lviv, Odesa, Mariupol, and Uzhhorod and their model values T{mod} are presented in Fig. 6, *a*, *c*. Note that for the cities of Kyiv, Dnipro, Kharkiv, and Zaporizhzhia with the «heat island» effect, the parameter ε{*R*} of the model ranged from 0.4 to 0.7 (see Table 2). A

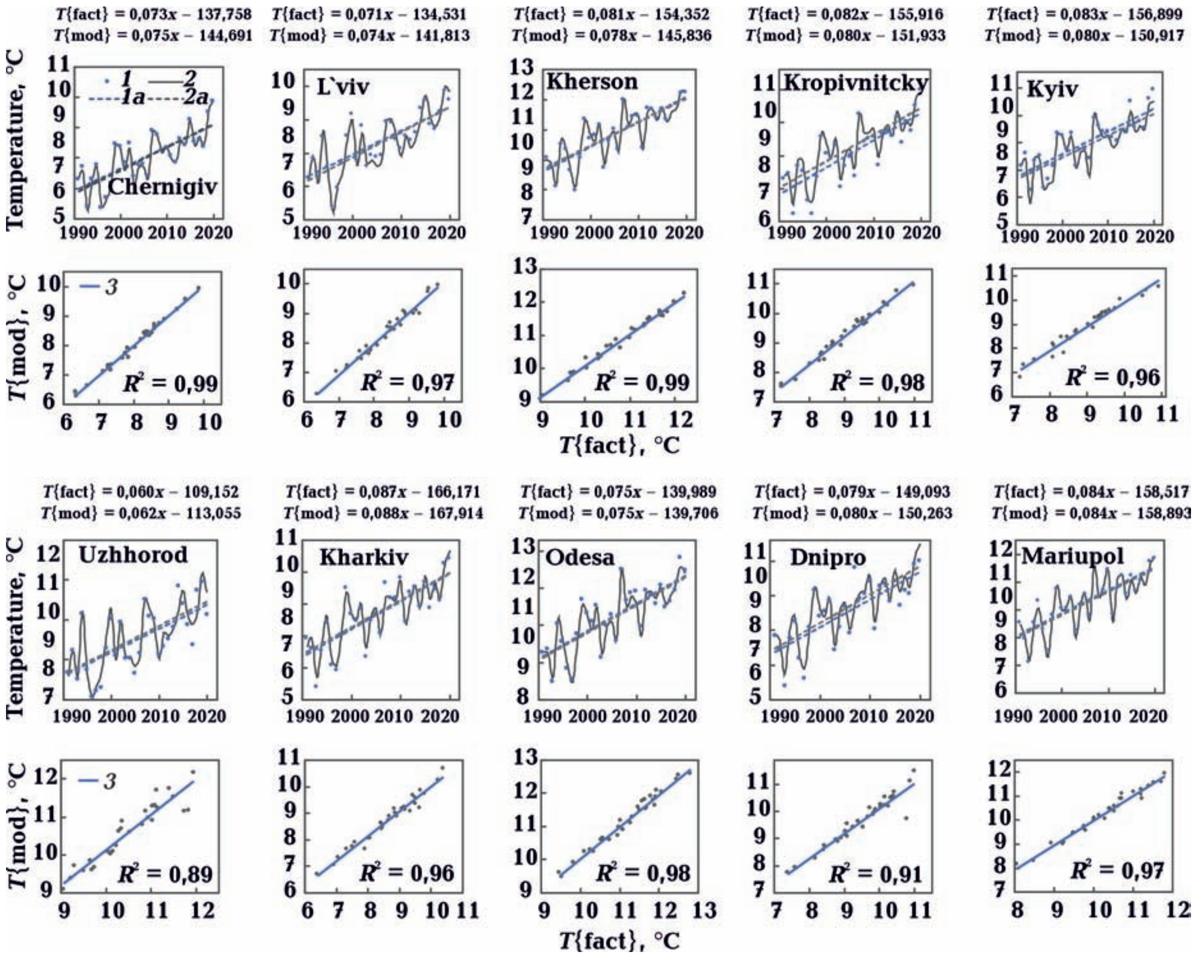


Fig. 6. Time course of average annual temperature *T*{fact} (*1*) and their model values *T*{mod} (*2*) recorded at 10 meteostations (*1a* and *2a* are linear trends) and (line of table *a*, *b*) a comparison of the model assessments *T*{mod} with their actual values *T*{fact} for the period 1991—2020 (*3* is linear regression, $R^2$ is reliability of the linear approximation).

comparison of $T\{\text{mod}\}$ with their actual values $T\{\text{fact}\}$ for these meteostations in 1991—2020 are presented in Fig. 6, *b*, *d* (the reliability of the linear approximation ($R^2$) is 0.89—0.98).

Similarly, the seasonal course of temperature is modeled for the set $\Omega_{72}$ yearly for 1991—2020.

However, this semi—empirical model showed a large scatter of the reconstructed data for 2/3 of the weather stations of Ukraine for 2007. This year, anomalous weather conditions have developed in all seasons. This problem was also discussed in [Busuioc et al., 2007; Rutishauser et al., 2008; Founda, Giannakopoulos, 2009; Unkašević, Tošić, 2011]. For this year, empirical data were used instead of model values.

**The validation of semi-empirical model average monthly temperature**. The parameterization method was validated by constructing semi-empirical models of the seasonal course of the average monthly surface temperature in Ukraine in 1991—2020 for ten additional meteostations not included in the general set for model [Boychenko et al., 2022]. This work showed that the model approximates the seasonal course of temperature and fits the process quite well.

Also, the semi-empirical model of the annual and seasonal course of temperature and precipitation was validated for the Volyno-Podolsk Height [Boychenko, Serdyuchenko, 2005].

In the future, we shall attempt the spatial interpolation of average annual and monthly temperatures for the territory of Ukraine at 0.1×0.1° latitude and longitude.

**Discussion.** ***Spatial interpolation methods of surface temperature.*** Interpolation methods of hydrometeorological parameters are often used to produce continuous surface data based on point observations. The common interpolation methods for surface temperature, precipitation, and sea surface temperature are Inverse Distance Weighted, Kriging, Natural Neighbor Interpolation and Spline [Kusuma et al., 2018; Piazza et al., 2015; Price et al., 2000; Skrynyk et al., 2020; Zhang, Von Storch, 2022].

A comparison of two methods for elevation-dependent spatial interpolation of climatic data from weather stations was presented by Price et al. [2000]. Thirty-year average monthly temperature and precipitation data from regions in western and eastern Canada were interpolated using thin—plate smoothing splines and a statistical method gradient plus inverse-distance-squared. It was noted that accuracy could be improved by introducing additional independent variables affecting the local climate. Also, Nalder and Wein [1998] showed that the method is a simple, robust, and accurate interpolation technique for estimating 30-year averages of monthly temperature and precipitation at specific sites in western Canada.

We used the radial basis function with thin plate splines early for spatial interpolation of the observations at the meteorological stations [Boychenko et al., 2018]. This function produced good interpolation results for gently varying values within a large distance [Boer et al., 2001; Hutchinson, 1995; Smith et al., 2017].

**Conclusions.** In this study, the regional semi-empirical model of the spatiotemporal distribution of the average annual and monthly temperature for the plain part of Ukraine on the basis of the methodology for assessing the influence of height above sea level and geographic coordinates is proposed. Based on themethod for determining the altitudinal, latitudinal, and longitudinal gradients of meteorological parameters, we calculated the gradients for annual and monthly air surface temperature for 1961—1990 and 1991—2020.

Thus, on the plain part of Ukraine, the annual surface air temperature decreases on average by 0.60—0.63 °C every 100 m above sea level, by 0.51—0.55 °C per 1 degree of latitude to the north, by 0.067—0.071 °C per 1 longitude degree to the east. Also, the variations of these annual mean temperature gradients from year to year in 1991—2020 are characteristic.

The seasonal variation of gradients has a pronounced non-monotonic character: the highest values of the altitudinal gradient are typical for July—August (–0.63÷–0.73 °C per 100 m), and the lowest — for April—May (from –0.45 to –0.55 °C per 100 m); the highest values of the latitudinal gradient are typical for August—September (from –0.60 to –0.70 °C per 1° N), and the lowest — for April—May (from –0.20 to –0.35 °C per 1° N); the longitudinal gradients have positive values in June—August (0.074—0.128 °C per 1° E) and negative values in November—March (from –0.228 to –0.154 °C per 1° E).

We found that the altitudinal and latitudinal gradients of temperature have the greatest spatiotemporal variability, and the longitudinal gradient has the smallest one. The greatest variabilities of temperature gradient values are typical for February—March and July—September and the least — for April—May.

The analysis of the dynamics of gradient changes in 1991—2020 compared to 1961—1991 showed the following: the altitudinal gradient values increased by 8—13 % in January and March—May; thelatitudinal gradient values increased by ~30 % in December—February and decreased by ~20 % in May—August.

In plain regions with uniform terrain with low relief, differences between actual and model values are negligible. However, one should consider the influence of additional effects associated with pronounced orographic and other terrain features. For these regions, the coefficient is introduced in the model depending on the proximity to mountains or seas and the magnitude of the «heat island» effect, etc.

The model estimates of 30-year monthly mean temperature in Ukraine for 1961—1990 and 1991—2020 were calculated. A comparison of the model estimates of climatic norms of the average annual and monthly temperature for 72 meteostations in Ukraine with their actual values showed a statistically significant correlation (the reliability of the linear approximation is 0.89—0.98). Thus, the presented semi-empirical model makes it possible to restore the annual and monthly temperatures on the territory of Ukraine quite well.

## References

Boer, E.P.J., De Beurs, K.M., & Hartkamp, A.D. (2001). Kriging and thin plate splines for mapping climate variables. *International Journal of Applied EarthTC Journal., 3*(2), 146—154. https://doi.org/10.1016/S0303-2434(01)85006-6.

Boychenko, S., Maidanovych, N., & Zabarna, O. (2022). Assessing the influence of height above sea level and geographic coordinates on surface air temperature values for a plain part of Ukraine. *European Association of Geoscientists & Engineers: 16th International Conference Monitoring of Geological Processes and Ecological Condition of the Environment* (pp. 1—5). https://doi.org/10.3997/2214-4609.2022580191.

Boychenko, S. (2008). *Semi-Empirical Models and Scenarios of Global and Regional Changes of Climate*. V. Voloshchuk (Ed.). Kyiv: Naukova Dumka, 310 p. (in Ukrainian).

Boychenko, S., & Serdyuchenko, N. (2005). Assessment of the dependence of the parameters of regional climatic fields on the height above sea level. *Geofizicheskiy Zhurnal, 27*(5), 858—867. https://www.researchgate.net/publication/342081987.

Boychenko, S., & Voloshchuk, V.M. (2007). Stochastic semi-empirical model of spatio-temporal transformation of the modern climate of Ukraine. *Dopovidi NAN Ukrainy,*(1), 105—111 (in Russian).

Boychenko, S., Voloshchuk, V., Kuchma, T., & Serdyuchenko, N. (2018). Long-time changes of the thermal continentality index, the amplitudes and the phase of the seasonal temperature variation in Ukraine. *Geofizicheskiy Zhurnal, 40*(3), 81—96. https://doi.org/10.24028/gzh.0203-3100.v40i3.2018.137175.

Busuioc, A., Dumitrescu, A., Soare, E., & Orzan, A. (2007). Summer anomalies in 2007 in the context of extremely hot and dry summers in Romania. *Romanian Journal of Meteorology, 9*(1-2), 1—17.

CGO: Central Geophysical Observatory of empirical data. (2021). Retrieved from http://cgo-sreznevskyi.kyiv.ua/index.php?lang=en&fn=u_klimat&f=ukraine&p=1.

Claps, P., Giordano, P., & Laguardia, G.(2008). Spatial Distribution of the Average Air Temperatures in Italy: Quantitative Analysis. *Journal of Hydrologic Engineering, 4*, 242—249. https://doi.org/10.1061/(ASCE)1084-0699(2008)13:4(242).

Daly, Ch., Gibson, W., Taylor, G., Johnson, G., &

Pasteris, P. (2002). A knowledge-based approach to the statistical mapping of climate. *Climate Research, 22*, 99—113. https://doi.org/10.3354/cr022099.

de Castro, M., Gallardo, C., Jylha, K., & Tuomenvirta, T. (2007). The use of a climate-type classification for assessing climate change effects in Europe from an ensemble of nine regional climate models. *Climatic Change, 81*, 329—341. https://doi.org/10.1007/s10584-006-9224-1.

Founda, D., & Giannakopoulos, C. (2009). The exceptionally hot summer of 2007 in Athens, Greece — a typical summer in the future climate? *Global and planetary change, 67*(3-4), 227—236. https://doi.org/10.1016/j.gloplacha.2009.03.013.

Habit, E., Zurita, A., Díaz, G., Manosalva, A., Arriagada, P., Link, O., & Górski, K. (2022). Latitudinal and Altitudinal Gradients of Riverine Landscapes in Andean Rivers. *Water, 14*, 2614. https://doi.org/10.3390/w14172614.

Hutchinson, M.F. (1995). Interpolating mean rainfall using thin plate smoothing splines. *International Journal of Geographical Information Systems, 9*, 385—403. https://doi.org/10.1080/02693799508902045.

Johansson, B. (2000). Areal Precipitation and Temperature in the Swedish mountains. An Evaluation from a Hydrological Perspective. *Hydrology Research, 31*(3), 207—228. https://doi.org/10.2166/nh.2000.0013.

Kusuma, D., Murdimanto, A., Sukresno, B., Jatisworo, D., & Hanintyo, R. (2018).Comparison of interpolation methods for sea surface temperature data. *Journal of Fisheries and Marine Science, 2*(2), 103—115.https://doi.org/10.21776/ub.jfmr.2018.002.02.7.

Lipinskyy, V., Dyachuk, V., & Babichenko, V. (Eds.). (2003). *The Climate of Ukraine*. Kyiv: Raevskyy Publishing, 344 p. (in Ukrainian).

Lookingbill, T.R., & Urban, D.L. (2003). Spatial estimation of air temperature differences for landscape-scale studies in montane environments. *Agricultural and Forest Meteorology, 114*, 141—151. https://doi.org/10.1016/S0168-1923(02)00196-X.

Marynych, O.M., & Stetsenko, E.I. (2006). Geographical encyclopedia of Ukraine. Kyiv: Publ. of the Institute of Encyclopedic Research of the National Academy of Sciences of Ukraine (in Ukrainian). Retrieved from https://esu.com.ua/article-29102.

Mcroberts, B., & Nielsen-Gammon, J. (2011). A New Homogenized Climate Division Precipitation Dataset for Analysis of Climate Variability and Climate Change. *Journal of Applied Meteorology and Climatology, 50*, 1187—1199. https://doi.org/10.1175/2010JAMC2626.1.

Nalder, I.A., & Wein, R.W. (1998). Spatial Interpolation of Climatic Normals: Test of a New Method in the Canadian Boreal Forest. *Agricultural and Forest Meteorology, 92*, 211—225. https://doi.org/10.1016/S0168-1923(98)00102-6.

Ninyerola, M., Pons, X., & Roure, J. (2000). A methodological approach of climatological modelling of air temperature and precipitation through GIS techniques. *International Journalof Climatology, 20*(14), 1823—1841. https://doi.org/10.1002/1097-0088(20001130)20:14<1823::AID-JOC566>3.0.CO;2-B.

Oliver, J.E. (Ed.). (2005). *Encyclopedia of World Climatology*. Berlin, Heidelberg, New York. Berlin: Springer Science & Business Media, 874 p.

Piazza, A., Conti, F., Viola, F., Eccel, E., & Noto, L. (2015). Comparative Analysis of Spatial Interpolation Methods in the Mediterranean Area: Application to Temperature in Sicily. *Water, 7*, 1866—1888. https://doi.org/10.3390/w7051866.

Price, D., Mc Kenney, D., Nalder, I., Hutchinson, M., & Kesteven, J. (2000). A comparison of two statistical methods for spatial interpolation of Canadian monthly mean climate data *Agricultural and Forest Meteorology, 101*, 81—94. https://doi.org/10.1016/S0168-1923(99)00169-0.

Rutishauser, T., Luterbacher, J., Defila, C., Frank, D., & Wanner, H. (2008). Swiss spring plant phenology 2007: Extremes, a multicentury perspective, and changes in temperature sensitivity. *Geophysical Research Letters, 35*(5). https://doi.org/10.1029/2007GL032545.

Serbin, S., & Kucharik, C. (2009). Spatiotemporal Mapping of Temperature and Precipitation for the Development of a Multidecadal Climatic Dataset for Wisconsin Journal of Applied *Meteorology and Climatology, 48*, 742—757. https://doi.org/10.1175/2008JAMC1986.1.

Skrynyk, O.A., Osadchyi, V.I., Szentimrey, T., Bihari, Z, Sidenko, V.P., Oshurok, D.O., Boichuk, D.O., & Skrynyk, O.Y. (2020). Spatial interpolation of climatological data with relief and physicogeographical peculiarities of the territory of Ukraine. *Ukrainian Geographical Journal, 110*, 13—19. https://doi.org/10.15407/ugz2020.02.013 (in Ukrainian).

Smith, T.B., Smith, N., & Weleber, R.G. (2017). Comparison of nonparametric methods for static visual field interpolation. *Medical &Biological Engineering & Computing, 55*(1), 117—126. https://doi.org/10.1007/s11517-016-1485-x.

*The Climate Cadastre of Ukraine (standard norms for the period 1961—1990), CGO*. (2005). Kyiv, 48 p. (in Ukrainian).

Tutmez, B., Kaymak, U., & Tercan, A.E. (2012). Local spatial regression models: a comparative analysis on soil contamination. *Stochastic environmental research and risk assessment, 26*(7), 1013—1023. https://doi.org/10.1007/s00477-011-0532-2.

Unkašević, M., & Tošić, I. (2011). The maximum temperatures and heat waves in Serbia during the summer of 2007. *Climatic change, 108*(1), 207—223. https://doi.org/10.1007/s10584-010-0006-4.

Voloshchuk, V., & Boychenko, S. (2003). Scenarios of possible changes of climate of Ukraine in 21th century (under influence of global anthropogenic warming). In Lipinskyy, V., Dyachuk, V., Babichenko, V. (Eds.), *The Climate of Ukraine* (pp. 308—331). Kyiv: Raevsky Publishing (in Ukrainian).

Vrac, M., Stein, M., Hayhoe, M., & Liang, X.-Z. (2007). A general method for validating statistical downscaling methods under future climate change. *Geophysical Research Letters, 34*, L18701. https://doi.org/10.1029/2007GL030295.

Zhang, M., & Von Storch, H. (2022). Determining Interannual Variability of the Annual Cycle. *Preprints*, 2022080319. https://doi.org/10.20944/preprints202208.0319.v1.

# Напівемпірична модель просторово-часового розподілу приземної температури на рівнинній частині території України

***С. Бойченко*[1], *Н. Майданович*[2], *2023***

[1]Інститут геофізики ім. С.І. Субботіна НАН України, Київ, Україна
[2]УкрНДІПВТ ім. Леоніда Погорілого, смт. Дослідницьке, Україна

Просторовий розподіл температури лінійно залежить від континентальності клімату, морфології рельєфу, положення регіону відносно морів, на додаток до звичайних показників висоти, широти та довготи. Існують інші фактори, які можуть мати додатковий значущий вплив: наявність великих водойм, рельєф, атмосферні чинники (місцева циркуляція), конфігурація та форма узбережжя і рослинність. Отже, ці багатофакторні впливи утворюють кліматичне поле температури.

У цьому дослідженні запропоновано регіональну напівемпіричну модель просторово-часового розподілу середньорічної та місячної температури для рівнинної частини України на основі методики оцінювання впливу висоти над рівнем моря та географічних координат. За цією методикою визначено висотні, широтні та довготні градієнти для річної та місячної приземної температури за періоди 1961—1990 та 1991—2020 рр. Так, на рівнинній частині території України річна приземна температура повітря знижується в середньому на 0,60—0,63 °C зі зсувом на висоту 100 м над рівнем моря, на 0,51—0,55 °C зі зсувом на один градус широти на північ, на 0,067—0,071 °C зі зсувом на один градус довготи на схід. Характерні також варіації цих середньорічних градієнтів температури від року до року від року до року.

Сезонна зміна градієнтів має виражений немонотонний характер: найбільші значення висотного градієнта характерні для липня—серпня (від –0,63 до –0,73 °C на 100 м), а найменші — для квітня—травня (від –0,45 до –0,55 °C на 100 м); найбільші значення широтного градієнта характерні для серпня—вересня (від –0,60 до –0,70 °C на 1° N), а найменші — для квітня—травня (від –0,20 до –0,35 °C на 1° N); довготні градієнти мають додатні значення в червні—серпні (0,074—0,128 °C на 1° E), і від'ємні значення в листопаді—березні (від –0,228 до –0,154 °C на 1° E). Встановлено, що висотний і широтний градієнти температури мають найбільшу просторово—часову мінливість, а довготній — найменшу. Найбільша мінливість значень температурного градієнта характерна для лютого—березня та липня—вересня, а найменша — для квітня—травня.

Аналіз динаміки зміни градієнта за період 1991—2020 рр. порівняно з періодом 1961—1991 рр. показав, що значення висотного градієнта зросли на 8—13 % у січні та березні—травні; значення широтного градієнта зросли на ~30 % у грудні—лютому та зменшилися на ~20 % у травні—серпні.

Запропонована напівемпірична модель містить коефіцієнт, який враховує вплив додаткових ефектів, пов'язаних з яскраво вираженими орографічними та іншими особливостями рельєфу. У нашому дослідженні наведено числові значення цього коефіцієнта для окремих мікрокліматичних районів рівнинної частини території України.

Розраховано модельні оцінки 30-річної середньомісячної температури в Україні за періоди 1961—1990 та 1991—2020 років. Порівняння модельних оцінок кліматичних норм середньої річної та місячної температури для 72 метеостанцій України з їх фактичними значеннями показало статистично значущий кореляційний зв'язок (достовірність лінійної апроксимації 0,89—0,98). Отже, дизайн напівемпіричної моделі дає змогу досить добре відновити річну та місячну температуру на території України.

**Ключові слова**: висотний, широтний та довготний градієнти, середньорічна та місячна температура, кліматична норма, напівемпірична модель.