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Long-time changes of the thermal continentality index, the amplitudes and the phase of the seasonal temperature variation in Ukraine

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Проаналізовано особливості просторово-часових варіацій індексів континентальності Gorczynsky та Johanson—Ringleb, а також амплітуди та фази сезонних варіацій температури на території України в умовах глобального потепління. Для аналізу використано довгострокові емпіричні дані (середньомісячна температура), що отримані на мережі метеорологічних станцій України, які рівномірно розташовані на рівнинній території України (з висотою над рівнем моря не більш як 350 м) за період 1900—2017 рр. Зміни амплітуди та фази сезонних варіацій температури досліджено за допомогою аналізу Фур'є. Встановлено, що на фоні загального зниження значень індексів континентальності клімату на території України за період 1900—2017 рр. (через значне потепління в холодний період року), спостерігається тенденція їх зростання (K_G на 6 % за 100 років і $K_{J—R}$ на 4 % за 100 років) за період 1970—2017 рр. (через підвищення температури в теплий сезон, особливо в травні—серпні). Амплітуда температури в XX ст. і на початку XXI ст. зменшилася на $-0{,}5\pm0{,}2$ °C за 100 років, а за період 1970—2017рр. інтенсивно підвищилася на $1{,}1\pm0{,}6$ °C за 100 років. Існує деяка тенденція до зміщення фази сезонних коливань температури, під впливом змін клімату. Так, ця фаза змістилася на $1{,}9\pm1{,}1$ дні у пізніші сезони в цілому для території України.

Ключові слова: зміна клімату, клімат України, термічний індекс континентальності, амплітуда і фаза сезонних варіацій температури.

Introduction. The global climate change over the past 100—150 years resulted in a spatial-temporal transformation of a number of climatic characteristics, for example, the amplitude of seasonal variations of surface temperature, the continentality index, the dryness or humidity index, etc. [Climate ..., 2013].

One of the modern regional features of climate change is spatial-temporal transformation of the amplitude of the seasonal temperature variation, due to sufficiently significant warming in the cold period of the year and somewhat lesser extent in summer, that led to decrease of climate continentalization (decontinentalization effect) [Climate ..., 2013], including in Ukraine [Voloshchuk, Boychenko, 2003].

Continentality is characterized by the large annual ranges of temperature and short lags between radiation and temperature [Oliver, 2005]. The degree of climate continentality is determined by the appearance of corresponding changes in the annual and daily amplitudes of the surface temperature, humidity, cloudiness, wind speed and atmospheric precipitation variability, etc.

In the latest century, various continentality climate indices were proposed, based on the dependence function between the annual temperature amplitude (annual range of temperature (January—July)) and the geographic latitude of a given place with different correction factors (thermal continentality index) [Khromov, Mamontova, 1974; Oliver, 2005].

The minimal continentality of climate is distinctive for oceanic territories, where the amplitude of the seasonal and diurnal temperature variation ranges from ~2—4 °C, and the maximum continentality is manifested in the depths of the continents to several tens of degrees.

A specific sectoral character of continentality is also manifested by heterogeneity in longitude direction due to the climate differences of the western and eastern parts of the continent (at the some latitude), but usually the influence of longitude is neglected.

Continentality of climate in mountain regions is not considered as due to the action of vertical zonality the aerothermal gradient effect is occurred (temperature decrease with altitude is about 6.5 °C/km), influenced by the latent and sensible turbulent heat flows, temperature inversion, the barrier effect of mountains (impact on precipitation values and winds), slope exposure (windward and leeward sides of the slope) and local winds (chinook, fohn, bora) [Oliver, 2005].

The thermal continentality index is one of the regional climate characteristics, which plays an important role in the analysis of changes in the distribution of natural and agrarian ecosystems under climate change [Buksha, 2009; Przybylak et al., 2010; Tkachenko, Boychenko, 2017].

The problem statement. The purpose of this study is to analyze the features of the space-time variations of the continentality indices, the amplitude and phase of the seasonal temperature variation in Ukraine under conditions of global warming.

Analysis of the latest researches and publication. Current occurrence of climate change has led to the development of a new cycle of analysis works about the continentality indices changes in different regions of the planet [Oliver, 2005].

The long-time changes of annual amplitude of temperature and the frost-free season as a function of climate continentality in USA for the period 1970—2009, 1940—1969, and 1900—1939 were researched in [Blaylock, 2012]. The general trend for USA to be that increasing oceanicity is associated with earlier last spring frosts, later first fall frosts, and longer frost-free seasons overall. These trends are present at the continental meteorological stations, but they are more pronounced in oceanic regions.

The spatial field of Conrad's index, the phase of the seasonal wave of temperature and the continentality index that is based on the shift of the seasonal variation of average temperature in meridional South America were represented in paper [Minetti, 1989]. It has been shown the phase of the first harmonic Fourier's, is a good climatic indicator of continental effects.

Temporal variation in the Johansson Continentality Index was examined for the period 1960—2013 over the Middle East and North Africa region [Ahmed et al., 2016]. The statistically significant increase in the continental conditions, but with considerable regional differences is established. So, the most rapid changes were found in the Fertile Crescent, the Nile Basin and the Ethiopian Highlands, while smaller changes occurred over the Arabian Peninsula, Sahara and Iran.

However, the researches, conducted in Europe are more interesting for us.

In accordance with the Gorczynsky and Conrad continentality indices, most of Europe is exposed to the maritime climate to the west and the continentality indices are increasing rather slow eastward and more rapidly in the mountains [Oliver, 2005; Mikolášková, 2009; Przybylak et al., 2010].

So, the spatial and temporal variability of the thermal continentality index for Central Europe (according to the weather data of Potsdam, Dresden, Prague, Vienna, Krakow and Debrecen) for the period of 1775—2012 is presented in [Ciaranek, 2014]. It is established that the continentality indices are the highest in Debrecen and the lowest in Potsdam. In the age-old course of continentality indices, two waves of their decline (in the late nineteenth century and in 1970s—1980s) and two waves of their growth (in 1930s—1940s, and also in the last 30—40 years) were noted.

In the Czech Republic the value of the continentality index (Gorczynsky), is 27.2 (it varied 17.5—40.0) for the period in 1961—2005 (the linear trend is only 0.08 for 10 years), and for the period of 1881—2006 also has no significant changes despite the year-by-year quite considerable fluctuations, which was shown in [Brázdil et al., 2008, 2009].

The studies presented in [Vilček et al., 2016], showed that the continentality indices (Gorczynsky, Conrad, Khromov, Ivanov) calculated for Slovakia for the period of 1961—2013 tend to the insignificantly increase, and hence a slight increase in the amplitude of the seasonal temperature variation.

The simulations with calculation of Gorczynsky and Conrad continentality indeces as a function of annual temperature range of the influence of the thermal properties of land surface on the Central European climate in the 21st century were suggested in [Szaby-Takács et al., 2015].

The studies of temperature regime changes in Ukraine during the 20th century using indicators of continental climate were conducted and annual amplitude of the air temperature were suggested in [Vrublevskaya, Kasadyuk, 2012; Boychenko et al., 2017].

Thus, the studies have shown that in Europe in the 20th century and at the beginning of the 21st century there was a general slight decrease in the continentality of the climate (due to warming in the cold period of the year) but the year-by-year quite considerable fluctuations were noted.

Materials and methods of research. There are many methods for determining the degree of climate continentality [Gorczynsky, 1922; Johansson, 1931; Conrad, 1946; Ivanov, 1959; Currey, 1974]. Most of them take into account the dependence of the annual amplitude of air temperature on the geographic latitude (an index is expressed as a percentage).

The two known continentality indices were used in the analysis:

• Gorczynsky (K_G) [Gorczynsky, 1922]:

$$K_G = 1.7\,\frac{A_*}{\sin\varphi} - 20 \qquad (1)$$

(marine — $0 \le K_G < 33$, continental — $33 \le \le K_G < 66$, extreme continental — $66 \le K_G < < 100$);

• Johanson—Ringleb ($K_{J—R}$) [Johansson, 1931]:

$$K_{J—R} = 0.6\left(1.6\,\frac{A_*}{\sin\varphi} - 14\right) - D + 36 \quad (2)$$

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

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

The continentality indices (1) and (2) differ somewhat: in the basis of the first, is the functional dependence of the annual temperature amplitude (to be more precise, annual range of temperature (January—July) from sinus of geographic latitude, and in se-cond, average values of the temperature for the seasons: autumn (September—November) and spring (March—May) is additionally taken into account.

In addition, the changes of the amplitude and the phase of the seasonal temperature variation were researched with the help of Fourier's analysis, namely:

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

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

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

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

$$A = \sqrt{a^2 + b^2}, \quad F = \operatorname{arctg}\frac{b}{a}, \qquad (3)$$

where k is the meteorological station number and m is the month number.

The long-term empirical data of the network of meteorological observation stations in the territory of Ukraine for the period of 1900—2017 were analyzed. The meteorological stations were chosen so that the following conditions were satisfied:

- observations by meteorological stations began no later than 1900;
- missing observations by meteorological stations do not exceed 30 % for the period of 1900—2017;
- stations are evenly located on the plains of Ukraine (the height above the sea level does not exceed 350 m).

Consequently 31 meteorological stations were chosen in the territory Ukraine, which met the requirements listed above.

The monthly series of temperature were subjected to a relative homogeneity test. The testing method is based on the determination of vertical, latitude and longitude gradients of meteorological parameters (by the Gauss method). This method of the observational data analyzing automatically removes the random heterogeneity and automatically homogenizes the series [Voloshchuk et al., 2002; Boychenko, Serdyuchenko, 2005].

The radial basis function with thin plate splines was used for spatial interpolation of the observations at the meteorological stations. The radial basis function produces good interpolation results for gently varying values within large distance [Hutchinson, 1995; Boer et al., 2001; Smith et al., 2017].

Features of climate change in Ukraine. The analysis of the meteorological observations data in Ukraine, showed, that in the 20th century the annual temperature increased by 0.5—0.7 °C per 100 years and the amplitude of the seasonal temperature variation decreased by ~ – 0.4 °C per 100 years [Boychenko, 2008]. The significant warming is typical during the cold period of the year and relatively insignificant in warm period of the year. Thus, the climate of Ukraine has become somewhat softer and the decontinentalization effect has appeared [Voloshchuk, Boychenko, 2003].

However, more significant warming is observed in the second half of the 20th century and at the beginning of the 21st century [Boychenko et al., 2016]. So, the annual temperature increased by 1.6 ± 0.4 °C per 100 years for the period 1900—2015. The average annual air temperature over the past twenty years (1991—2010 years) increased by 1.0 ± 0.2 °C compared to the 1961—1990 average [Buksha, 2009].

Repeatedly the new record levels of maximal average monthly temperature were recorded in Ukraine for the last 100 years. The repeatability and duration of summer heat periods increased (with the temperature higher than 25—30 °C) [Boychenko et al., 2017]. The droughts began to take place more frequent and in larger territories.

The insignificant increase of the annual sums of precipitation (5—7 % for 100 years) was recorded [Boychenko, 2008]. Also, the effect of alignment of a climatic field of the annual precipitation sums was revealed: in northern and northwestern regions of Ukraine, where the annual sum of precipitation was relatively high (650—750 mm/year), it decreased approximately by 10—15 %; in southern and southeastern regions, where the annual sum of precipitations was relatively low (350—450 mm/year), it increased approximately by 10—15 %.

Taking into account the established tendencies of the transformation of the climatic fields of annual surface temperature and annual sums of precipitation in the territory of Ukraine for the 20th century [Voloshchuk, Boychenko, 2003] and the possible scenarios of future global climate changes (RCP4.5 ($\Delta T \sim 2.0$ °C) and RCP8.5 ($\Delta T \sim 4.0$ °C)) [Climate ..., 2013], the regional scenarios of the possible climate changes to 2050 were developed, namely [Boychenko et al., 2016]:

scenario 1: it is likely not to exceed ($\Delta T \sim 1.4 \pm 0.2$ °C) and increase of the annual precipitation sums by 10 ± 5 % and the climate aridity in the warm period of the year (May and August);

scenario 2: it is likely to exceed ($\Delta T \sim 2.4 \pm 0.3$ °C) and differential spatial distribution of annual precipitation sums, namely the increase in northern, northwestern and northeastern regions by 15 ± 5 % and decrease in southern, southeastern and southwestern regions by 15 ± 5 %.

The contrast in precipitation sums between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions.

Features of the space-time variations of the continentality indices and the amplitude of the seasonal temperature. It is known, that the space-time distribution of the surface temperature on the plane in the territory of Ukraine possesses features of a temperate continental climate [Lipinskyi et al., 2003]. The continentality of climate is increasing towards the north and northeast of the country (deep into the continent).

One of the features of typical mid-latitude continental seasonal variation of temperature is the minimum in January and the maximum in July, with the conspicuous annual range of temperature A_*. On the average across the territory, the difference in annual temperature range (January—July) in the 20th century fluctuated within 25.5 ± 2.0 °C [Vrublevskaya, Kasadyuk, 2012; Boychenko et al., 2017].

Additionally, by calculation the Gorczynsky (K_G) and Johanson—Ringleb (K_{J-R}) continentality indices we also conducted the analysis of the space-time fluctuations of the amplitude of the seasonal temperature variation (A) and the phase (F), calculated using the Fourier analysis of average monthly observation data for Ukraine.

The results of the Gorczynsky (K_G) and Johanson—Ringleb (K_{J-R}) continentality indices calculations by equations (1) and (2) for 31 meteorological stations showed that: $K_G = 36.7 \pm 6.2$ for the period of 1900—2017 and $K_{J-R} = 59.7 \pm 3.6$ and $K_G = 35.4 \pm 6.1$, $K_{J-R} = 59.3 \pm 3.6$ for the period of 1970—2017. The amplitude of the seasonal temperature variation has the following values: $A = 12.6 \pm 1.1$ for the period of 1900—2017 and $A = 12.3 \pm 0.9$ for the period of 1970—2017.

The average values of the continentality indices and the amplitude of the seasonal temperature variation (A) for the periods of 1900—2017 and 1970—2017 for some meteorological stations are presented in Table. Therefore, the maximum values of the amplitude of seasonal temperature variation are distinctive for the northeastern regions, so as the minimum values for the southwestern regions of Ukraine.

The analysis of the continentality indices for the 20th century and the beginning of the 21st centuries showed a general tendency to decrease the values of the indices and the amplitude of temperature (due to the warming in the cold period of the year), whereas for the period of 1970—2017, the increasing tendency is revealed (due to a temperature rise in the warm period of year, especially in May—August). So, in general for Ukraine the continentality indices have a decreasing tendency (K_G by 2 % per 100 years and K_{J-R} by 0.1 % per 100 years) the period of 1900—2017, and on the contrary for the period of 1970—2017 the indices va-

The spatial-temporal distribution of continentality indices (K_G) and ($K_{J—R}$) and amplitude (A) and phase (F) of seasonal temperature variation in the territory of Ukraine for the periods of 1900—2017 and 1970—2017

Meteostation	Latitude, degree	Longitude, degree	Altitude, m	Continentality indices, %				Amplitude temperature (A), °C		Phase (F), month	
				Gorczynsky (K_G)		Johanson—Ringleb ($K_{J—R}$)					
				1900—2017	1970—2017	1900—2017	1970—2017	1900—2017	1970—2017	1900—2017	1970—2017
Chernivtsi	46,63	32,57	54	34,7 ± 7,3* – 1,4**	33,0 ± 6,5 9,08	58,8 ± 4,1 – 0,7	58,0 ± 3,8 6,2	12,0 ± 1,2 – 0,3	11,6 ± 1,0 1,6	1,30 ± 0,08 0,01	1,31 ± 0,07 0,07
Dnipro	48,6	34,97	143	40,8 ± 7,7 – 1,3	39,5 ± 7,5 4,4	62,3 ± 4,4 0,3	62,1 ± 4,4 2,3	13,8 ± 1,2 – 0,3	13,5 ± 1,0 1,0	1,29 ± 0,08 0,04	1,31 ± 0,07 0,03
Kharkiv	50,85	34,67	181	39,7 ± 8,0 – 0,3	38,9 ± 8,2 3,1	62,4 ± 4,7 0,5	62,2 ± 5,0 1,6	14,0 ± 1,3 – 0,3	13,7 ± 1,2 0,7	1,31 ± 0,08 0,04	1,33 ± 0,08 0,03
Kherson	49,97	36,13	155	40,4 ± 6,8 – 0,9	39,3 ± 6,7 11,9	60,7 ± 4,1 1,0	61,0 ± 3,9 5,6	12,9 ± 1,2 – 0,3	12,7 ± 1,0 2,0	1,25 ± 0,08 0,04	1,28 ± 0,07 – 0,01
Kropyvnytskyi	50,40	30,57	167	38,2 ± 7,9 – 0,9	37,0 ± 7,7 6,6	60,8 ± 4,6 0,4	60,6 ± 4,6 3,8	13,2 ± 1,3 – 0,3	12,9 ± 1,1 1,1	1,29 ± 0,08 0,03	1,31 ± 0,07 0,04
Kyiv	47,80	35,02	112	35,0 ± 7,9 0,1	33,8 ± 7,7 8,6	59,3 ± 4,6 0,9	59,0 ± 4,6 5,4	12,9 ± 1,3 – 0,3	12,5 ± 1,1 1,5	1,30 ± 0,09 0,04	1,33 ± 0,07 0,06
Lutsk	50,7	25,5	232	37,4 ± 7,8 0,5	36,6 ± 7,2 5,7	60,8 ± 4,6 1,0	60,7 ± 4,6 2,7	13,4 ± 1,2 – 0,3	13,1 ± 1,1 0,2	1,30 ± 0,09 0,06	1,33 ± 0,08 0,02
Odesa	50,7	25,5	232	37,7 ± 6,2 – 0,4	36,9 ± 5,4 11,5	58,1 ± 3,8 0,7	58,2 ± 3,4 8,2	12,2 ± 1,1 – 0,5	11,9 ± 0,9 1,9	1,19 ± 0,08 0,04	1,21 ± 0,07 0,11
Simferopol	46,43	30,77	42	36,5 ± 5,7 4,3	37,7 ± 5,5 8,8	58,1 ± 3,6 2,5	59,0 ± 3,2 3,4	11,1 ± 1,1 0,6	11,2 ± 0,9 1,9	1,21 ± 0,08 0,02	1,22 ± 0,07 – 0,07
Sumy	44,68	34,13	181	38,1 ± 8,0 – 1,2	37,0 ± 8,3 – 0,4	61,5 ± 4,8 0,1	61,2 ± 5,0 – 0,1	13,8 ± 1,3 – 0,7	13,4 ± 1,2 – 0,1	1,30 ± 0,08 0,05	1,33 ± 0,07 0,01
Ternopol	49,53	25,67	329	31,8 ± 6,8 – 1,9	30,2 ± 7,3 10,5	57,1 ± 3,91 – 0,2	56,6 ± 4,3 6,3	11,8 ± 1,1 – 0,4	11,5 ± 1,1 1,6	1,28 ± 0,07 0,04	1,30 ± 0,07 0,07
Zhytomyr	50,23	28,73	224	33,1 ± 7,9 – 0,3	31,9 ± 7,7 6,2	58,1 ± 4,5 0,2	57,7 ± 4,5 3,4	12,3 ± 1,2 – 0,3	12,0 ± 1,1 0,9	1,30 ± 0,09 0,03	1,31 ± 0,07 0,09
Zaporizhzhia	50,23	28,73	224	41,7 ± 7,3 – 4,5	39,5 ± 7,4 5,8	62,5 ± 4,2 – 1,8	61,6 ± 4,4 3,6	13,7 ± 1,1 – 0,9	13,3 ± 1,1 1,4	1,28 ± 0,07 0,04	1,30 ± 0,07 0,04
Ukraine (average for 31 stations)				36,7 ± 6,2 – 1,58	35,4 ± 6,1 6,0	59,7 ± 3,6 – 0,1	59,3 ± 3,6 3,6	12,6 ± 1,1 – 0,5	12,3 ± 0,94 1,1	1,28 ± 0,07 0,04	1,30 ± 0,07 0,06

* — the average for the period, ** — the coefficient of linear trend, normalized for 100 years.

lues are increased (K_G by 6 % per 100 years and $K_{J—R}$ by 4 % per 100 years). The temperature amplitude is decreased by $-0.5 \pm \pm 0.2$ °C per 100 years for the period of 1900—2017 and intensively increased by 1.1 ± 0.6 °C per 100 years for the period of 1970—2017.

The variations of the continentality indices K_G, $K_{J—R}$ and A for the period of 1900—2017 in Ukraine are shown in Fig. 1. As we can see, some cycles are observed in their century course: a decrease in 1905—1920, 1940—1960, 1975—1995 and an increase in 1920—1940, 1960—1975 and 1995—2017 with the range of ~5—10 %.

Truly, such periods of fluctuations in the continentality indices and the amplitude of the seasonal temperature variation were observed throughout in the 20th century and at the beginning of the 21st century.

The increase of the values of continentality indices and the amplitude of seasonal temperature variation for the last 30—45 years are noted, which is associated with increase in the frequency of anomalously high temperatures, especially in summer are noted. It has been suggested, that in accordance with our earlier hypothesis, this is the result of the shifting of the northern periphery of the subtropical anticyclones zone, including, to the territory of Ukraine [Voloshchuk, Boychenko, 2003].

About the dependence of amplitude of seasonal temperature variation on latitude, longitude, and altitude above sea level. The climatic characteristics of the meteorological elements of the region depend on the geographic coordinates and altitude of the terrain above sea level, which therefore constitute a set of multifactorial climatic fields, and the microscale features of the terrain where the stations are located and generate a certain "microclimatic noise" [Voloshchuk et

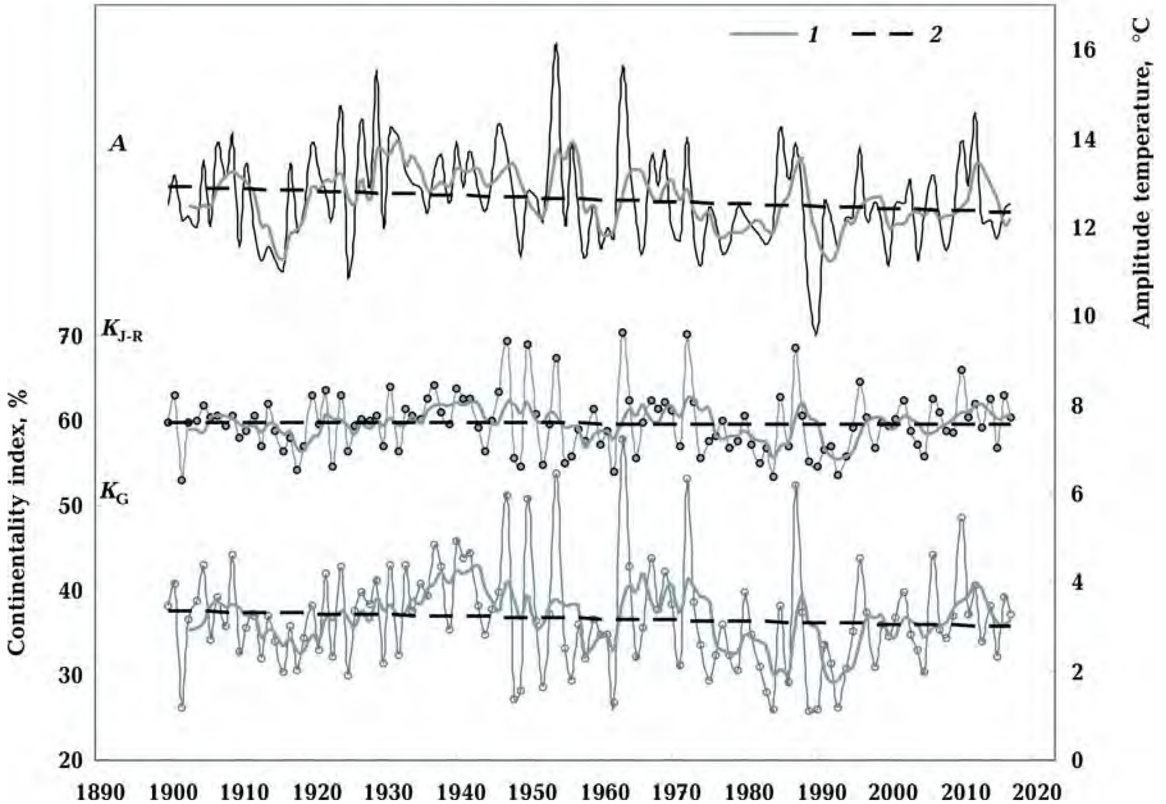


Fig. 1. Long-time changes of the thermal continentality index the amplitudes of seasonal temperature variation in Ukraine in the 20th century and at the beginning of the 21st century (*1* — sliding averaging, *2* — linear trend).

al., 2002; Boychenko, Serdyuchenko, 2005].

Analysis of the latitude, longitude and altitude distributions of the amplitude of the seasonal temperature variation (A) for the period of 1961—1990 in the territory of Ukraine was showed, that it varies by 0.10 °C per 1° latitude, by 0.15 °C per 1° longitude and by −0.3 °C per 100 m height above sea level [Boychenko, 2017] (Fig. 2).

Phase shift of seasonal temperature variation. Insolation, which is the main climate-forming factor, has a clearly expressed zonal distribution with typical seasonal variations [Oliver, 2005]. The features of the distribution and properties of the earth's surface and seas, as well as the circulation of the atmosphere, have a definite effect on the amplitude of the annual temperature of the region and cause a shift in the thermal wave in accordance with the radiative wave, there by forming its asymmetry, and changing its sinusoidal type.

The harmonic oscillation parameter F is the criterion of asymmetry and shift of the seasonal variation of average temperature with consideration the first harmonic the phase F (see equation (3)).

In studies conducted for the Southern Hemisphere [Minetti, 1989], it was shown that at a temperature regime with a maximum in January and a minimum in July, the phase F for a sinusoidal wave is 1.57 (from 1.81 to 1.03). According to the values of the phase F, Minetti's classified the climate as follows: if the values are above 1.55 it is the continental climate, 1.29—1.55 it is the coastal and transitional climate and less than 1.29 it is the marine climate.

With regard to the position of the maximum and minimum of heat wave for a given region, it shifts from 15 days to one month in continental regions and from 15 days to two months in the oceanic regions. There is a certain shift in year-to-year changes, in particular in the position of the maximum in December or February and the minimum in June or August. It has been shown, that the phase of the first harmonic of the seasonal wave of temperature is a good climatic indicator of continental effects.

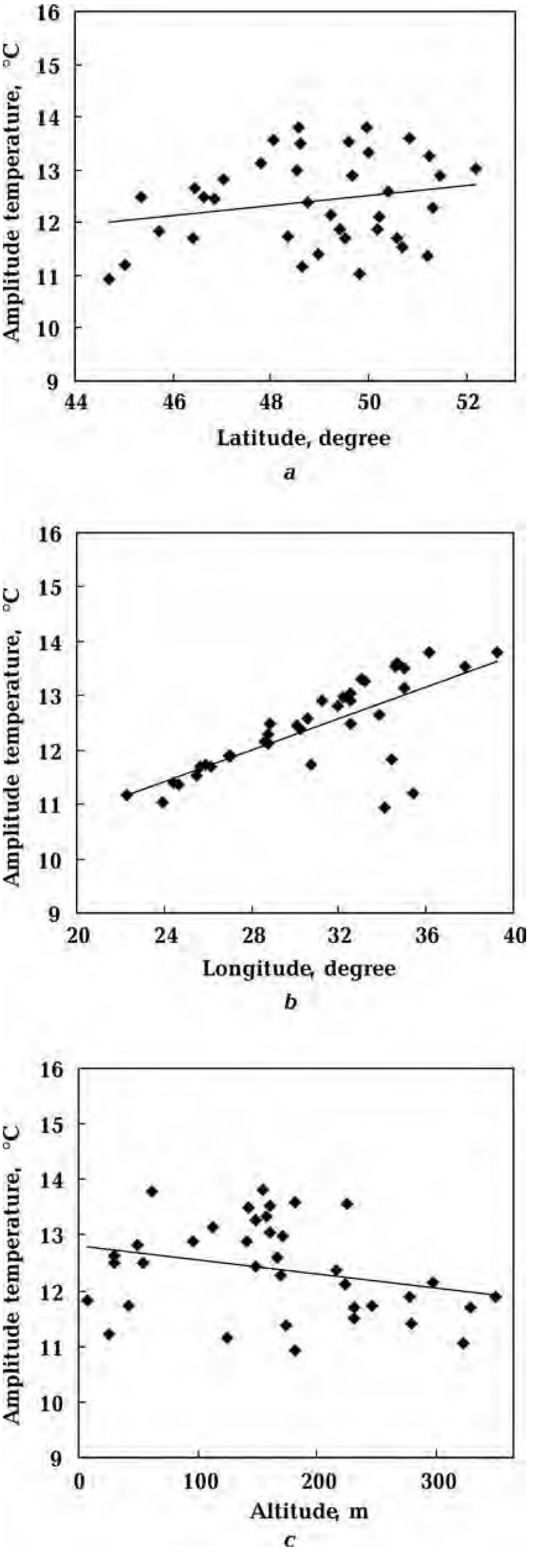


Fig. 2. Dependence of the amplitude of seasonal temperature variation from latitude (a), longitude (b) and height above sea level (c) on the territory of Ukraine (average for the period 1961—1990).

The conducted studies of the seasonal temperature variation for the territory of Ukraine showed that the asymmetry and the phase shift are distinctive also. The phases of seasonal temperature variation are $F = 1.28 \pm 0.07$ for the period of 1900—2017 and $F = 1.30 \pm 0.07$ for the period of 1970—2017 (F, unit of measure per month) (see table). The maximum and minimum of the phase of the seasonal temperature variations are formed around 19—28 of January and 19—28 of July.

In accordance with the climate classification by Minetti's, based on a changes of the parameter F, the territory of Ukraine is transitional from continental to the marine type. Apparently, for the Northern Hemisphere, the climate classification by the shift of the seasonal temperature variation taking into account the phase F, should be clarified.

The analysis of the parameter F changes in the territory of Ukraine showed a slight increase in the range from 0.01 to 0.08 for 100 years (0.04 for 100 years) for the period of 1900—2017 and a slight increase in the range from −0.04 to 0.11 for 100 years (0.06 for 100 years) for the period 1970—2017.

There are some trends in the phase shift of the seasonal temperature variation under the climate change impact, so the phase shifts are 1.9 ± 1.1 days in later seasons in general for the territory of Ukraine.

The variation of the phase shift of the seasonal temperature variation on the territory of Ukraine for the period of 1900—2017 is shows on Fig. 3. The maximum value of the parameter F is characteristic for the northwestern regions, and the minimum values are in the southern regions of Ukraine.

Some asymmetry and phase shift of seasonal temperature variation are the cause of climate change. In publication [Stine et al., 2009] it is noted, that the trend of temperature amplitude is negative, and is associated with the observation that in winter on average warms up faster than in summer and that leads to a displacement of the amplitude phase.

The phase trend of the annual surface temperature cycle on hemisphere shifts to earlier seasons by 1.7 days between 1954 and 2007, however, it contrast to the direction that are observed for central England and other regions. The tendencies these parameters on hemisphere are significant, but at the regional level are disjointed.

The spatial-temporal distribution of continentality indices (K_G) and ($K_{J—R}$), amplitude (A) and phase (F) of seasonal temperature variation in the territory of Ukraine (the average for the periods 1900—2017) and trends of these parameters are shown in Fig. 4.

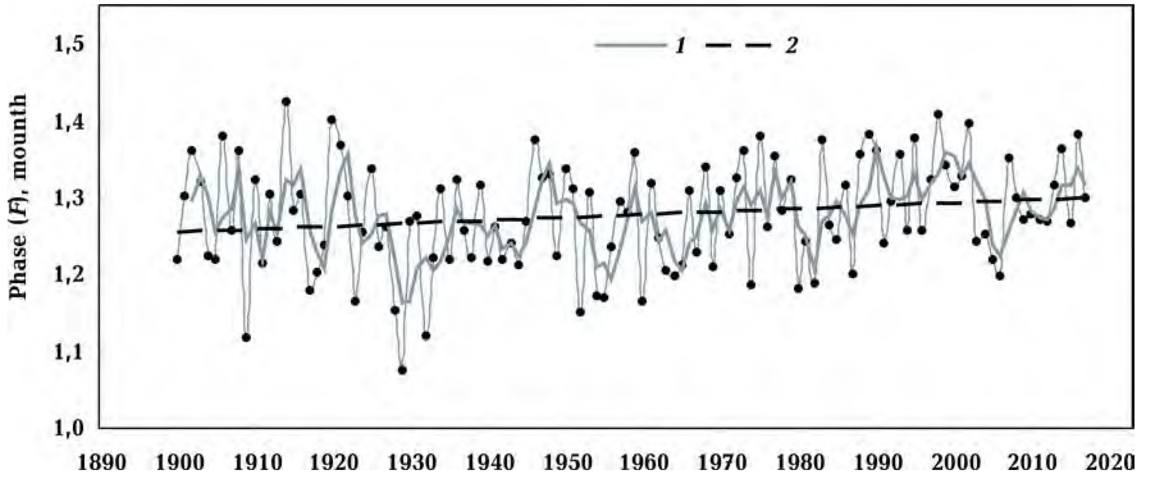
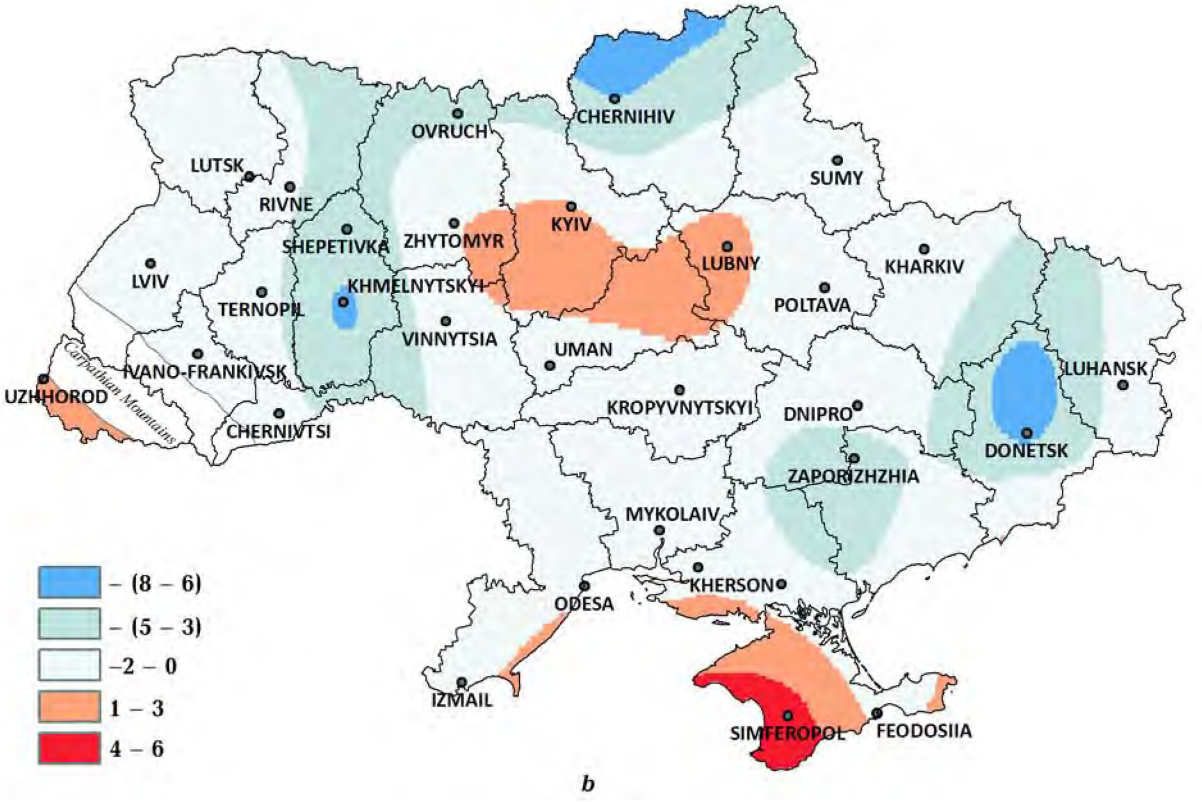


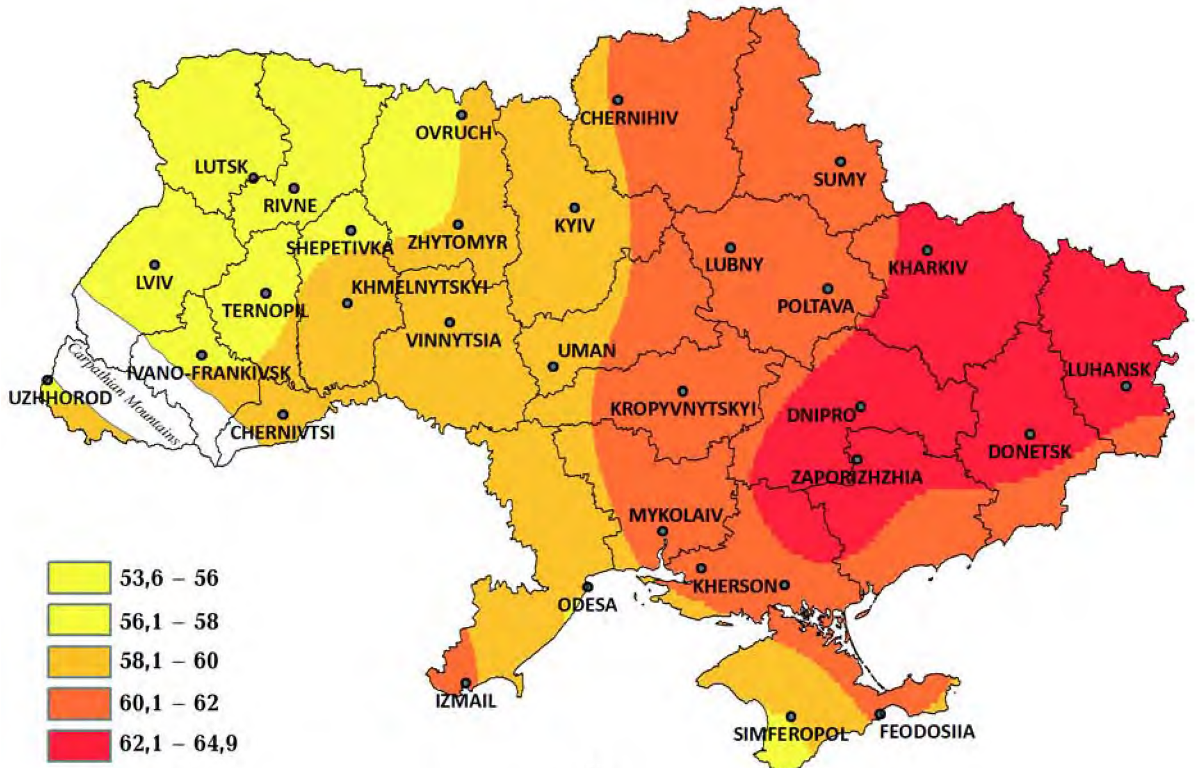
Fig. 3. Long-time changes of the phase of seasonal temperature variation in Ukraine for the 20th century and at the beginning of the 21th century (*1* — sliding averaging, *2* — linear trend).

a



b

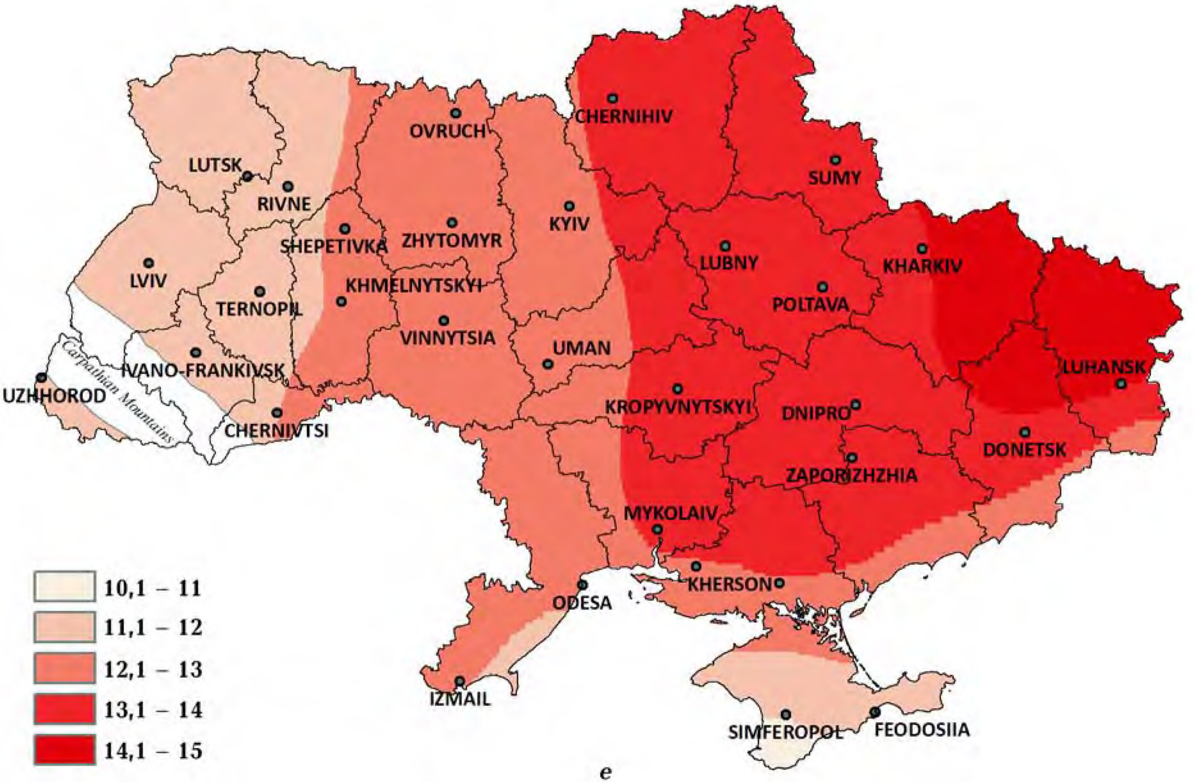
Fig. 4. The spatial-temporal distribution of continentality indices K_G (*a*) and $K_{J—R}$ (*c*) and amplitude A (*e*) and phase of seasonal temperature variations F (*g*) on the territory of Ukraine for the periods of 1900—2017 and trends of these parameters (*b*, *d*, *f*, *h*).



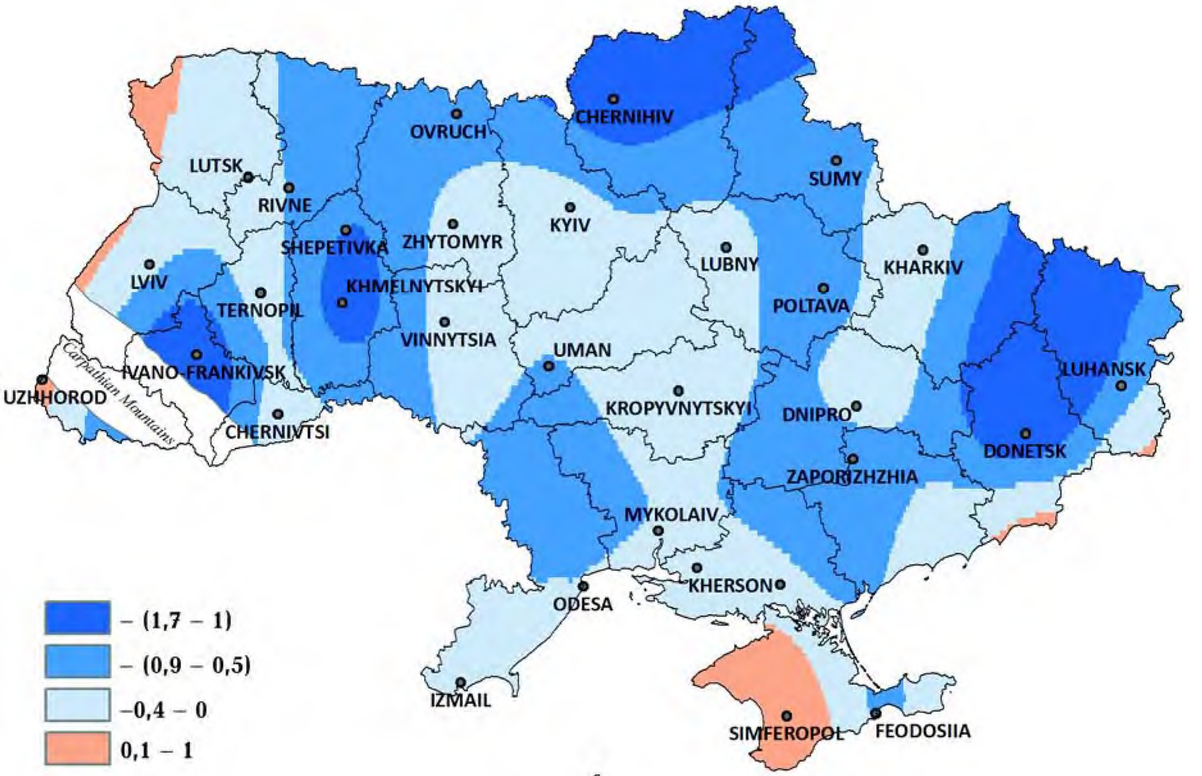
c

d

Продолжение Fig. 4 (Fig. 4, c, d).

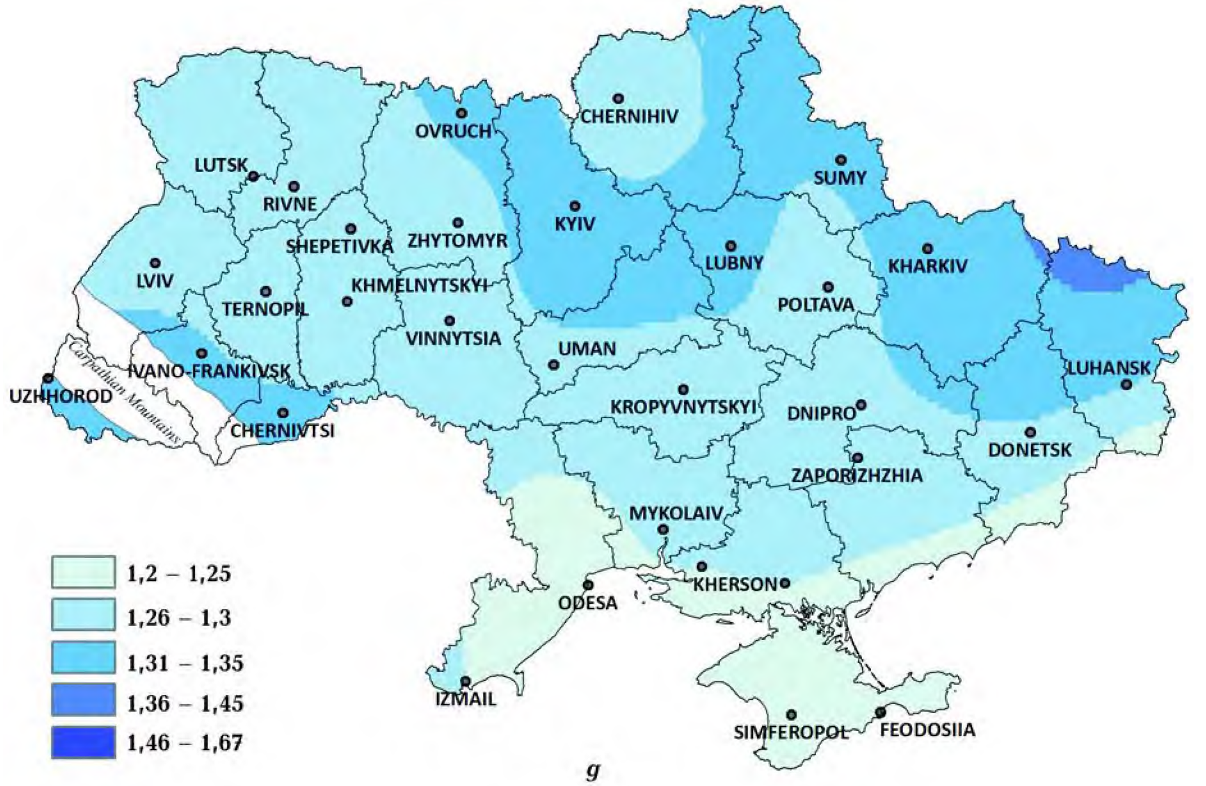


e

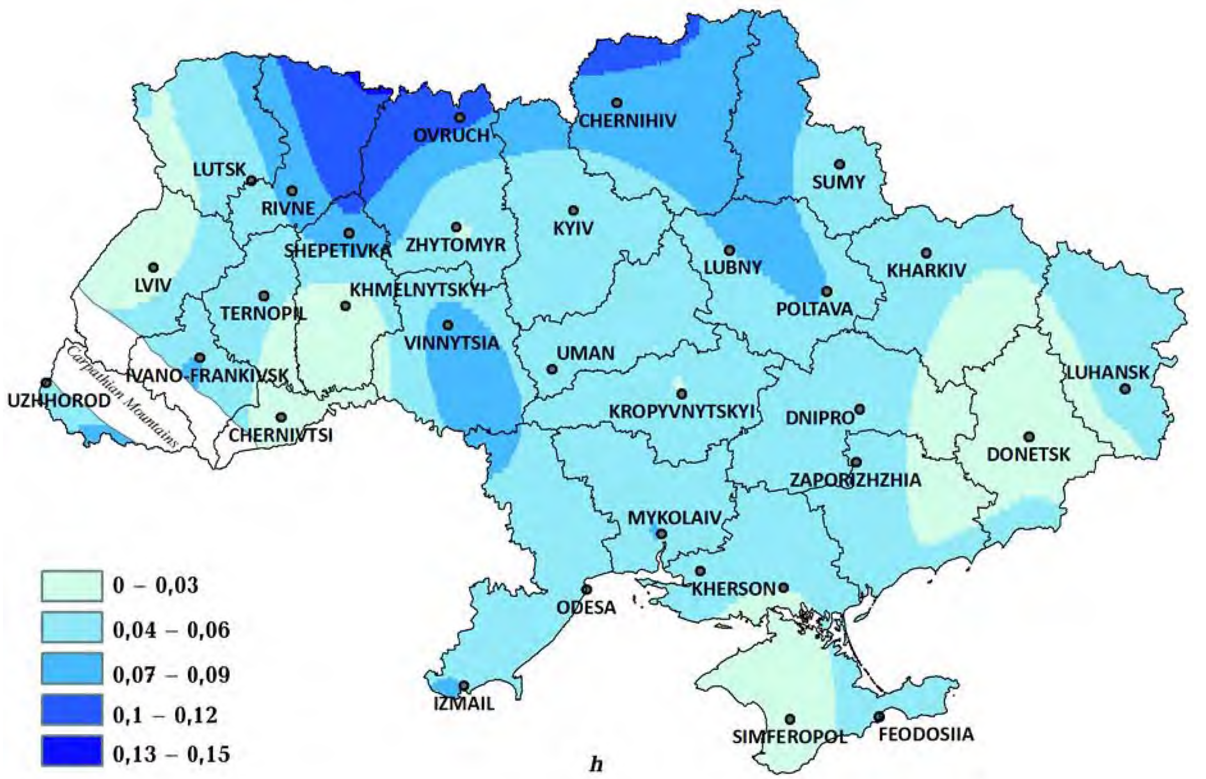


f

Продолжение Fig. 4 (Fig. 4, e, f).



g



h

Продолжение Fig. 4 (Fig. 4, g, h).

Conclusions. The features of the space-time variations of Gorczynsky and Johanson—Ringleb continentality indices, as well as the amplitude and phase of the seasonal temperature variation in the territory of Ukraine under conditions of the global warming were analyzed.

The long-term empirical data (average monthly temperature) of the network of meteorological observation stations in the territory of Ukraine that are evenly located on the plains of Ukraine (the height above the sea level is not exceeding 350 m) for the period of 1900—2017 were analyzed.

It was established that against the background of a general decrease in values of the continentality climate indices in the territory of Ukraine for the period of 1900—2017 (due to the significant warming during the cold period of the year), there are the increasing trends (K_G by 6 % per 100 years and $K_{J—R}$ by 4 % per 100 years) for the period of 1970—2017 (due to the temperature rise in the warm season, especially in May—August). The amplitude of temperature for the 20th century and at the beginning of the 21st century decreased by -0.5 ± 0.2 °C per 100 years, and in the period of 1970—2017 intensively increased by 1.1 ± 0.6 °C per 100 years. There were some trends of phase shift of the seasonal temperature variation under the climate change impact, so the phase shifts are 1.9 ± 1.1 days in later seasons in general for the territory of Ukraine.

Noted, that the increase of the continentality indices values and the amplitude of temperature for the last 30—45 years, is associated with the increase in the frequency of anomaly high temperatures, especially in summer. It has been suggested, that in accordance with our earlier hypothesis, it is possible, this is the result of the shift of the northern periphery of the subtropical anticyclones zone, including to the territory of Ukraine.

Long-time changes of the thermal continentality index, the amplitudes and the phase of the seasonal temperature variation in Ukraine

S. Boychenko, V. Voloshchuk, T. Kuchma, N. Serdyuchenko, 2018

Special features of spatial-temporal variations of continentality indices Gorczynsky and Johanson—Ringleb as well as an amplitude and phase of the seasonal change of temperature in the territory of Ukraine under conditions of global warming have been analyzed. Long-term empirical data (average month temperature) have been used obtained in the net of meteorological stations of Ukraine evenly located in the plain territory of Ukraine (height not more than 350 m above sea level) during the period 1900—2017. The changes of amplitude and phase of seasonal temperature variations were studied with the help of Fourier analysis. It has been found that against the background of general decrease of the values of continentality indices of the climate in the territory of Ukraine during the period 1900—2017 (due to considerable warming in the cold period of the year) increasing tendencies (K_G by 6 % per 100 years and $K_{J—R}$ by 4 % per 100 years) are observed for the period 1970—2017 (due to temperature growth during warm season, especially in August). Temperature amplitude in the 20th century and at the beginning of the 21st century decreases by $-0.50.2$ °C during 100 years, and during the period 1970—2017 increases intensively by 1.1 ± 0.6 °C during 100 years. Some trend of the shift of the phase of seasonal temperature fluctuations under the influence of climate changes exists because the phase has displaced by 1.9 ± 1.1 days during later seasons as a whole for the territory of Ukraine.

Key words: climate change, climate of Ukraine, thermal index of continentality, amplitude and phase of seasonal fluctuations of temperature.

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