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Steppe Ecosystem Functioning of East European Plain under Age-Long Climatic Change Influence

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Abstract

Background: The directed climate change is one of the most important global challenges of the XXIst century, which is beyond the scope of scientific research and makes a complex interdisciplinary problem. **Methods:** The object of study is the long-term changes of climatic conditions in the southern subzone of the East European Plain steppe. The subject of research is the temporal regularities of climatic parameters development (air temperature, total amount of precipitation). **Results:** The results of processing and forecasting changes for long-term climatic indexes parameters (ambient temperature and precipitation) that reflect the age-long rhythm of the of steppe ecosystem development of the East European Plain southern part. Using the multivariate statistics the regularities of long-term climate dynamics are obtained. The main rhythms are specified, the abnormal manifestations, the main time period changes and the functions of climate indicator provision are determined. The probabilities of annual inertia and periodic climatic changes using Markov networks are calculated. **Conclusion:** The highly accurate prediction of climate change is implemented on the basis of nonlinear multilayer artificial neural networks.

Keywords: Air Temperature, Climate Change, Markov Chains, Precipitation, Steppe Ecosystems, Time Series Analysis

1. Introduction

The directed climate change is one of the most important global challenges of the XXIst century, which is beyond the scope of scientific research and makes a complex interdisciplinary problem, encompassing environmental, economic and social aspects of countries sustainable development[1]. The climate changes are diverse and appear, in particular, in the intensity, frequency, climate anomaly frequencies and extreme weather events on different levels of the hierarchy in space and time. This brings the mankind to continuous adaptation of its all activities in a changing world. Scientists specify the main causes of global climate change: anthropogenic factor[1,2], carbon dioxide circulation increase[3]; radiative heating of the atmosphere due to infrared radiation absorption at the dominating influence of convective heat transfer[4], the change of currents in the Arctic Ocean (the cold Labrador current in the area of Greenland and warm Gulf Stream), which leads to periodic catastrophic periods of stable temperature reduction and increase in the Northern Hemisphere[5,6]. The climate at the regional level is influenced by the three most important factors: the atmosphere circulation, the solar insolation and relief [7,8].

The climate change problem is presented in the works of many scientists:[9-14]. Concerning the East European Plain conditions the authors studied the age regularities (XVIII-XX centuries) of climatic factor influence on hydrological processes[15,16], the transformation of agricultural landscapes in different types of river basins[17,18]. The analysis of available sources showed that the development potential of new approaches to climate change modeling and forecasting is preserved.

2. Methods

The object of study is the long-term changes of climatic conditions in the southern subzone of the East European Plain steppe. The subject of research is the temporal regularities of climatic parameters development (air

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temperature, total amount of precipitation). In southern Ukraine the Black Sea area is bounded by 400 mm isohyet the Lower Danube to the Azov Sea coast, the center of which has the hydro-meteorological station Kherson with a long series of observations. The study uses the actual data on annual values of surface air temperature (T, ºC) and total precipitation (P, mm) for Kherson station and the archival data for a continuous period of observations restoration which lasted for 112 years (1900–2011). The climatic standards for the specified period made: $\overline{T}$ = 9.8 °C; $\overline{P}$ = 400 m. These parameters characterize in general the southern steppe conditions of the East European Plain.

The following research methods are applied in the article for a comprehensive preliminary analysis, the evaluation and determination of the series heterogeneity and temporal regularities development of the climatic conditions: descriptive statistics, regression analysis and the transformation of variables (T4253N-smoothen, the method of different integral curves for the modular ratio). In order to determine the cyclic components and identify the largest periodogram values for time series development the method of one-dimensional Fourier analysis was used. In order to estimate the climate inertia probability of inertia we used the method of Markov chains. The probability of climatic condition periodic changes was determined by the Gabriel and Neumann methods. In order to predict the probability characteristics of climate formation in time we used a non-linear method of multilayer Artificial Neural Networks (ANN). The comparative analysis of the developed models reliability was performed using the statistical evaluation criteria of forecasting reliability with independent test samples for the purpose of the data approximation by the best model for prediction. The subordinate modules Time Series and Forecasting (TSF) and Neural Networks of the licensed software STATISTICA 10.0 were used for the analysis, modeling and forecasting of the climatic parameters dynamics.

3. Discussion

Within the individual parts of the East European Plain The zonal change of landscapes on the Earth surface is conditioned by the influence of various prevailing factors of differentiation: in the northern part (taiga-forest area), where precipitation exceed the evaporation value it's the thermal factor; in the southern part (with semi humid and semiarid climate) it's a moisturizing factor. The background characteristics of the heat and moisture provision conditions reflect the specific conditions and age old rhythm aero-hydro-thermal conditions for instrumental period. However, the internal integrity of the Holocene (Subatlantic period) final part allows to extend the average climate data of instrumental period for cal 2800 BP[19].

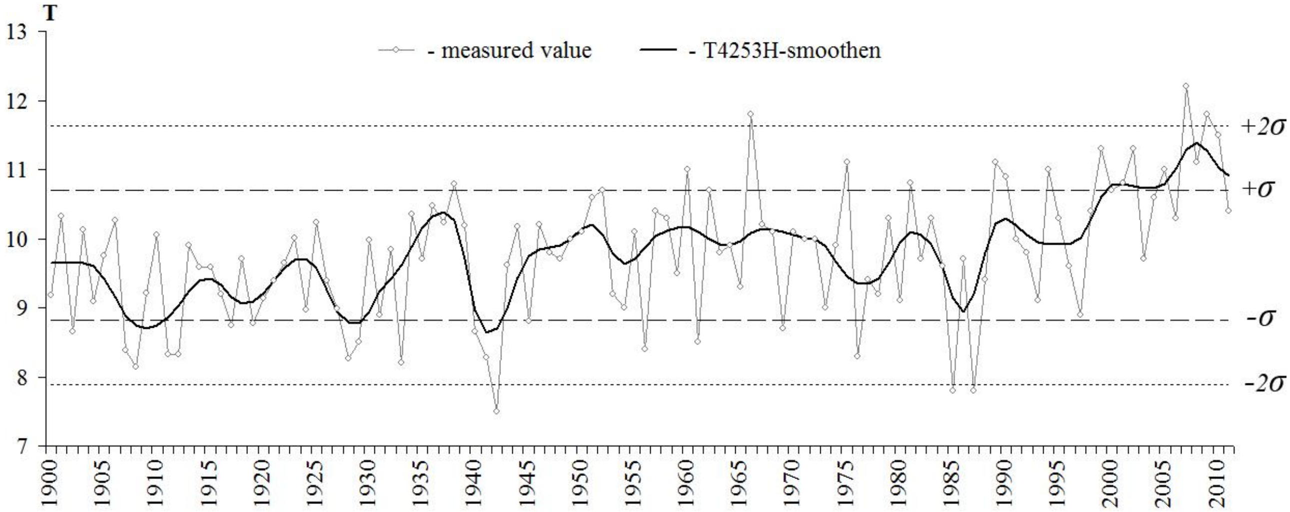
In order to determine the general laws of the climatic conditions temporary formation, the actual values of meteorological data were transformed using "T4253N-smoothen» (Figure 1). This filtering method enables to obtain a smooth row preserving the main characteristics of the original empirical series. Throughout the whole period of air temperature dynamics observation there is a positive trend, the extremum of which occurs at the beginning of the XXI-st century (the small cyclical component is equal to 2 years, the average cyclical component makes 9 years and the large cyclical component makes 37 years). Using the Fourier method the long-term 2, 11 and 22-year cycles of moistening conditions formation with a positive trend component are determined.

Abnormal climatic conditions according to the studied parameters were determined by the following criteria: $T, P \geq \pm\sigma$ – strong and $T, P \geq \pm 2\sigma$ very strong anomalies, where σ is the standard deviation value. At the normal distribution of a random variable (mean annual temperature T, the amount of annual precipitation P) the following relations are performed:

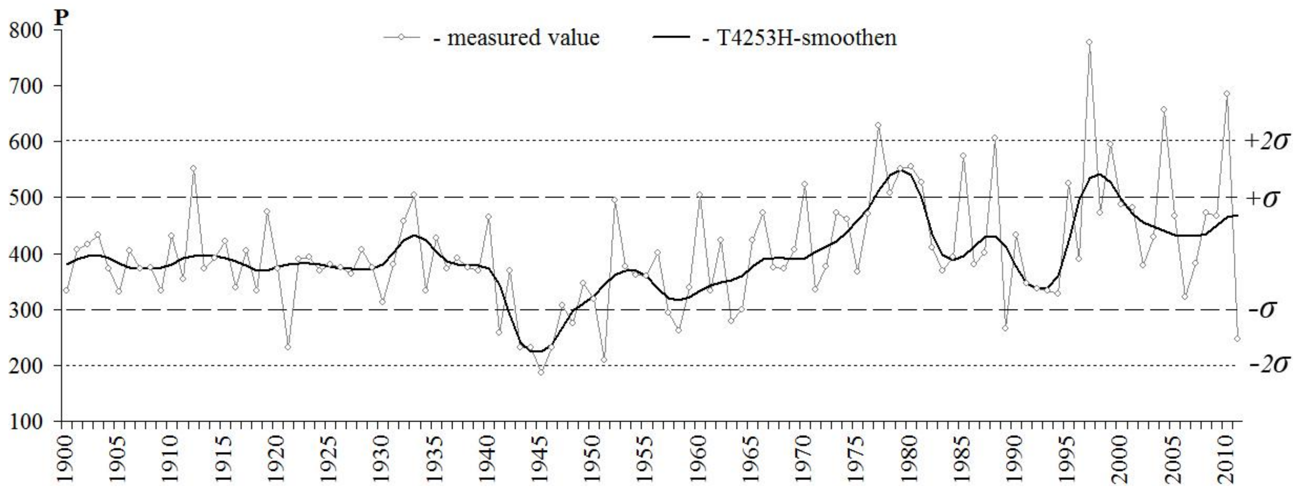
$$\begin{cases} p(-\sigma < T < +\sigma) = 0.651, \\ p(-2\sigma < T < +2\sigma) = 0.946, \\ p(-\sigma < P < +\sigma) = 0.723, \\ p(-2\sigma < P < +2\sigma) = 0.946, \end{cases}$$

where p - the event probability, in this case it's the probability of threshold values not exceeding the anomalies of mean annual temperature (T) and annual precipitation amount (P).

Thus, in 65% of cases the absolute value of the mean annual air temperature anomaly does not exceed the value σ, i.e. for more than a century period the strong anomalies lasted for 39 years (35%) and very strong anomalies lasted for 6 years (5%) concerning the temperature mode in the South Eastern European Plain. Over the past 20 years the average annual temperature increased by 1.0 °C (from 9.6 to 10.6 °C). The absolute value of the annual precipitation anomalies is estimated at 72%: the strong anomalies lasted for 31 years (28%) and very strong anomalies lasted for 6



(a)



(b)

Figure 1. Long-term dynamics of climatic parameters concerning the weather station Kherson: **(a)** the average annual air temperature (T, °C); **(b)** the amount of precipitation per year (P, mm).

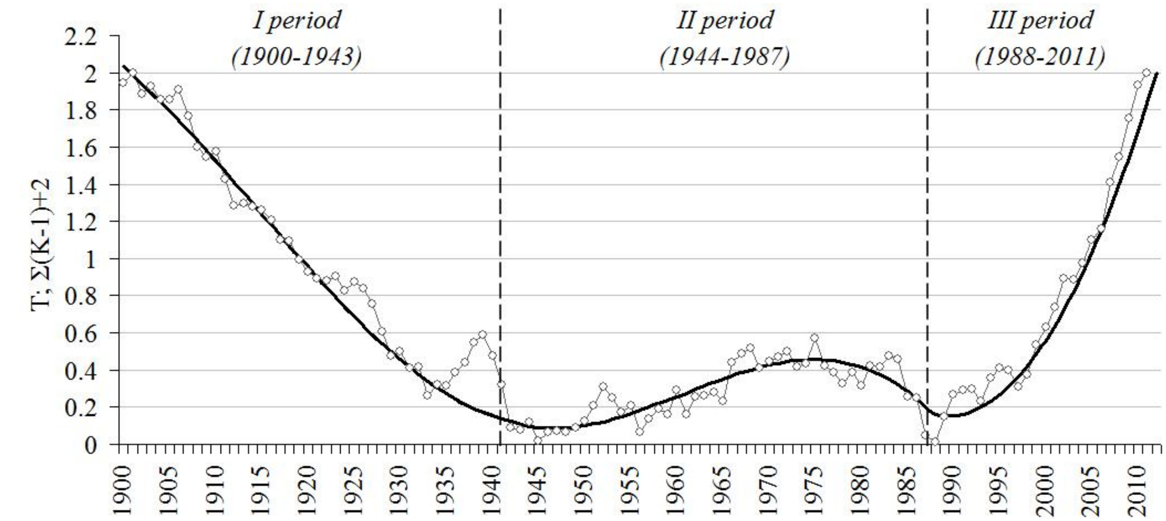
years (5%). Over the past 20 years, the amount of precipitation increased by 69 mm per year (from 387 to 456 mm).

Three major periods of climate change are identified as the conversion result of historical data using the difference of the integral curves of modular factors (Table 1, Figure 2).

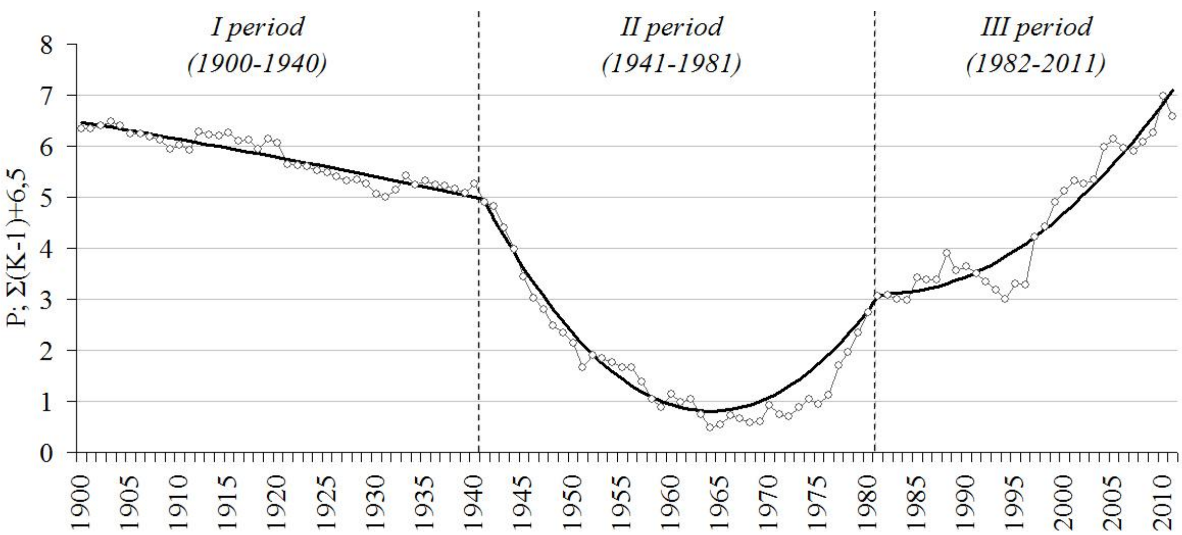
The calculation was performed and probability curves were developed (Figure 3) in order to determine the likelihood of certain climatic parameter values recurrence on the basis of historical data.

This study results showed the average annual change of long-term annual average climate conditions during the last two historical periods within the year (Fig. 4). During the last 70 years the manifestations of warming over the first 10 months of the year are observed by 2 °C (from 10.4 to 12.4 °C) on the average, the amount of precipitation increase by 90 mm (from 314 to 404 mm). On the main background of precipitation increase 75% of all months demonstrate negative anomalies of mean monthly and, in some cases, of mean semi-annual precipitation rate, leading to disastrous floodwater areas at local and regional levels.

Using Markov chains allowed to determine the climate annual inertia probability. Thus, the likelihood of air temperature recurrence was more than a cyclical norm of PT = 0.54, the annual precipitation amount PP = 0.48.



(a)

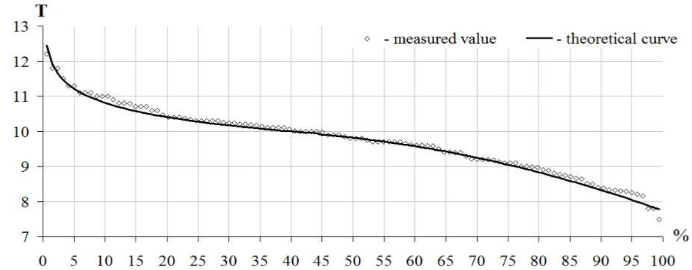


(b)

Figure 2. Graphical substantiation of the main periods for climatic parameters development according to the Kherson weather station Kherson: a) the average annual air temperature;

Table 1. Models of climate indicators development for major periods

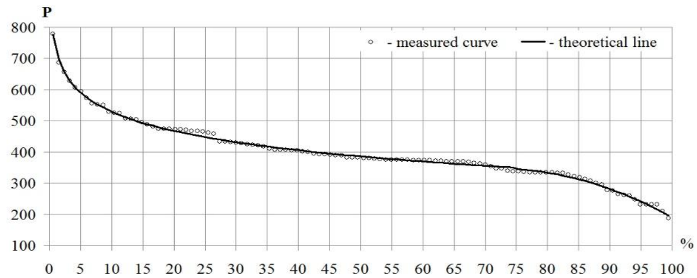
Periods	Optimal function	Approximation level (R^2)
Average annual temperature		
I – 1900–1943 ($\overline{T}$ = 9,3 °C)	$T = 0.0005t^2 - 0.0682t + 2.1736$	0.97
II – 1944–1987 ($\overline{T}$ = 9,8 °C)	$T = -0.00003t^3 + 0.0018t^2 - 0.0143t + 0.1168$	0.75
III – 1988–2011 ($\overline{T}$ = 10,6 °C)	$T = 0.0036t^2 - 0.0171t + 0.1726$	0.98
Total amount of precipitation per year		
I – 1900–1940 ($\overline{P}$ = 389*m*)	$P = -0.0001t^2 - 0.0323t + 6.5018$	0.87
II – 1941–1981 ($\overline{P}$ = 379*m*)	$P = 0.0075t^2 - 0.3879t + 5.6583$	0.97
III – 1982–2011 ($\overline{P}$ = 447*m*)	$P = 0.0045t^2 - 0.0014t + 3.096$	0.91



$$f(T)=\begin{cases}\int\limits_{0,1}^{45} -1.294\log 10(S)+12.16di \\ \int\limits_{45}^{100} -0.0004S^2+0.0244S-9.70di\end{cases}$$

$r=0.996;\ r^2 = 0.993$

1-a *1-b*

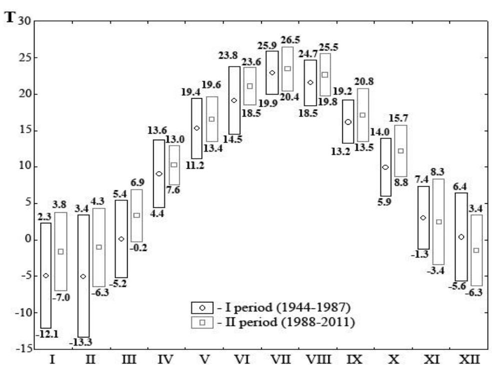


$$f(P)=\begin{cases}\int\limits_{0,1}^{75} -205.63\log 10(S)+734.95di \\ \int\limits_{75}^{100} -0.199S^2+28.618S-682.67di\end{cases}$$

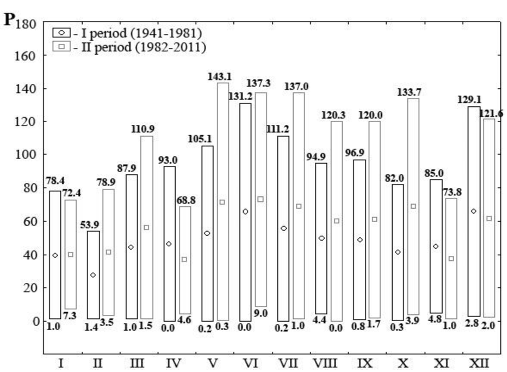
$r=0.998;\ r^2 = 0.996$

2-a *2-b*

Figure 3. Empirical curve **(a)** and climatic parameter provision function **(b)**: 1 - the average annual temperature, °C; 2 - the annual precipitation, mm.



(a)



(b)

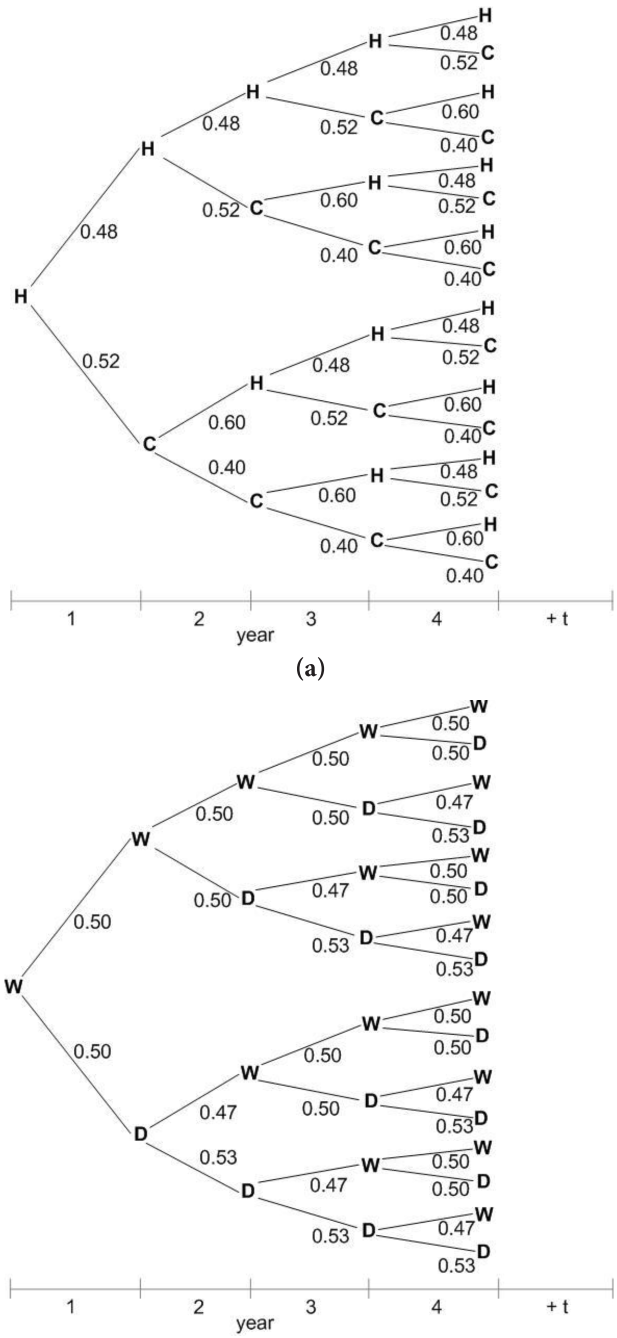
Figure 4. Long term annual changes of climatic conditions, months: **(a)** air temperature (T), °C; **(b)** total annual precipitation (P), mm.

The inertial likelihood of hot (H) years recurrence makes PH1 = 0.48, and the hot years after cold ones makes PH2 = 0.60. Consequently, the probability that a cold year will begin after a hot one makes (C) PC1 = 0.52, and similarly the probability that at one cold year will be followed by another cold year makes PC2 = 0.40. The inertial likelihood of wet years recurrence (W) made PW1 = 0.50, the wet years recurrence after dry ones made PW2 = 0.47. Consequently, the probability of a dry year after a wet one makes (D) PD1 = 0.50, and similarly the probability that one dry year is followed by another dry one makes PD2 = 0.53. The chain of climatic change probabilities is shown by Figure 5.

The probability of hot and rainy periods in t years is equal to the probability of cold and dry years, respectively, repeated every (t + 1) years, that is[20]:

$$P_{S(H;W)} = (1-p_1)p_1^{t-1}$$
$$P_{S(C;D)} = p_2(1-p_2)^{t-1}.$$

Consequently, the probability of an isolated annual hot year is equal to $0,52p_1^{1-1}$, the probability of three year hot period makes 0.12, the probability of five year hot period makes 0.03, etc. The probability of cold periods of the same duration makes 0.60, 0.10, 0.02, respectively. The



(a)

(b)

Figure 5. Probabilities of climatic condition changes (hot (H), cold (C), dry (D), wet (W) years) as a schematic representation of Markov chains: **(a)** ambient temperature, **(b)** annual precipitation.

probability an annual isolated wet year makes $0,50p_1^{1-1}$, the probability of a three-year wet period makes 0.12, the probability of a five year wet period makes 0.03, etc. The probability of dry periods with the same duration is equal to 0.60, 0.13, 0.04, respectively. The Markov chains developed on the basis of meteorological observations show that the hot periods lasting for 3–5 years are more likely than the same cold periods, and 3–5 year periods without rain are more likely than the rainy periods. This means the cyclical increase of the mean annual air temperature and the amount of annual precipitation decrease in the southern steppe of the East European Plain.

The probability of hot-cold and wet-dry periods alternation with different duration is determined by the formula:

$$P_{pt} = \frac{(1-p_2)^{t-1} - p_1^{t-1}}{(1-p_2-p_1)} p_2(1-p_1).$$

The probability values of various duration periods were obtained after calculations. The alternation of hot and cold periods: t = 2, P_{pt} = 0.312; t = 3, P_{pt} = 0.275; t = 4, P_{pt} = 0.182; t = 5, P_{pt} = 0.107; t = 6, P_{pt} = 0.059. The alternation of wet-dry periods: t = 2, P_{pt} = 0.235; t = 3, P_{pt} = 0.242; t = 4, P_{pt} = 0.187; t = 5, P_{pt} = 0.129; t = 6, P_{pt}= 0.083.

ANN [22] architectures of three- and four-layer perceptron were developed to predict climate changes:

- Air temperature forecast: the four-layer perceptron with eight neurons in the first hidden layer and eight neurons in the second hidden layer (Table 2), the method of learning: the inverse distribution (450 epochs), the ANN matrix consists of 168 weighting coefficients;
- Precipitation forecast: a three-layer perceptron with seven neurons in the hidden layer (Table 2), the method of study: inverse distribution (100 epochs) and related gradients (28 epoch), ANN matrix consists of 91 weight coefficients.

The optimal parameters of ANN training algorithm for climatic parameters prediction are: the training speed ratio within η = 0.07–0.22; training moment ratio (inertia ratio) α = 0.4; the number of iterations (epochs) prior to memorizing within N = 30–40; the number of iterations (epochs) for ANN training within N = 130–170 (depending on the sample array and predicted values development complexity). The number of hidden layers and network neurons is determined for each time series individually. The neuron activation function is the sigmoid one. The ANN accuracy for climatic parameters prediction within an independent (test) sample made: 84% according to the average annual air temperature and 78% according to the precipitation amount.

Table 2. Key features of neuromodels for climatic indicator change prediction in the steppe of the East European Plain

ANN criteria	ANN approximation parameters
	Annual average ambient temperature
Weighting coefficient correction function	$E(w(t)) = \frac{1}{2}\left(f\left(\sum_{j=1}^{7} w_j^{(2)}(t) f\left(\sum_{n=1}^{12} w_n^{(1)}(t) x_n^{(t)} \right)\right) - d^{(t)} \right)^2$
Network response function	$y_i(t) = f\left(\sum_{j=1}^{7} w_j^{(2)}(t) f\left(\sum_{n=1}^{12} w_n^{(1)}(t) x_n^{(t)} \right)\right)$
Training algorithm	$w_{ni}(t+1) = 0,07\delta_i x_n(t) + 0,4(w_{ni}(t) - w_{ni}(t-1))$
	Annual precipitation amount
Weighting coefficient correction function	$E(w(t)) = \frac{1}{2}\left(f\left(\sum_{j=1}^{7} w_j^{(2)}(t) f\left(\sum_{n=1}^{12} w_n^{(1)}(t) x_n^{(t)} \right)\right) - d^{(t)} \right)^2$
Network response function	$y_i(t) = f\left(\sum_{j=1}^{7} w_j^{(2)}(t) f\left(\sum_{n=1}^{12} w_n^{(1)}(t) x_n^{(t)} \right)\right)$
Training algorithm	$w_{ni}(t+1) = 0,22\delta_i x_n(t) + 0,4(w_{ni}(t) - w_{ni}(t-1))$

Note:
t – time series discrete value;
w – weighting coefficient matrix;
$x_n^{(t)}$ – n-th coordinate of the input vector at a given time moment t;
$yi(t)$ – i-th coordinate of the output vector that is developed by the neural network at a certain time moment t;
$d_n^{(t)}$ – i-th coordinate of the actual output vector at the time moment t;
$f(si)$ – hidden layer neurons activation function: $\mathrm{f(s)} = \frac{1}{1+\mathrm{e}^{-\mathrm{s}}}$ – sigmoidal with data conversion range[0, 1];
η – neural network training speed ratio;
α – training moment ratio (inertia ratio) of neural networks.

The cyclical fluctuations of climate lasting for several decades (11-, 29–45-, 75–80 year cycles), seem to be related with the fluctuations of non-evolutionary nature for geosystems. This is especially true for lesser duration cycles: an annual one, reflecting the change of seasonal geographic phenomena, a 2-year-old one (usually making 26-month) in tropospheric and stratospheric parameters, 5-6-year-old ones, observed in the geographical and meteorological phenomena[21]. All of these variations (with a specific time period of less than 10 years) is more logical to refer not to climate changes, but to long weather anomalies[21]. The search of not regular but probable properties is reasonable for them.

Often at synchronous bioclimatic evaluation the air temperature changes and the amount of precipitation are in an antiphase, i.e., for example, when a wet rich period does not correspond to more heat and vice versa. The presence of such periods is established during the study of the 100-year series of instrumental climate observations. It is important to note that the simple characteristics of heat and humidity provision for landscape zones and many complex values have a low relation with bioclimatic responses in the ecosystems due to inadequate reflection of hydrothermal factor synergy effect, especially for marginal zones of their change amplitude. This disadvantage may be overcome by using bioenergetic approach, in which non-trivial non-linear presentations about bioclimatic relations were used.

4. Conclusion

1. The assessment of age-long climate changes in the southern steppe of the East European Plain showed that within the present conditions of climate development a stable dynamic increase of mean annual air temperature and the amount of annual precipitation increase occurs. During the observation period 39 years (35%) with strong temperature anomalies and 6 years (5%) with very strong temperature anomalies are determined, which led to the increase of mean annual air temperature by 1.0 °C. The absolute value of annual precipitation anomalies over 112 years of observations made 33%. The average annual temperature and the total precipitation amount in the southern part of the East European Plain for more than a century duration is characterized by three main periods: the period of decrease (beginning of the twentieth century), the period of stabilization or equilibrium (the middle of the twentieth century) and climatic parameter increase (the end of the XX-th and the beginning twenty-first century). The study of annular climate change features showed that the manifestations of warming during the first 10 months is observed by 2 °C, and for the period from May to October the increase of mean annual precipitation amount by 90 mm was marked.
2. With the use of Markov chains the cycle properties of climatic parameters were determined. The inertial likelihood of hot year recurrence is estimated at 0.48, and hot years recurrence after cold ones makes 0.60. The inertial likelihood of wet years recurrence made 0.50 years after the corresponding recurrence of the wet ones after dry ones made 0.47. It was found that the hot periods lasting for 3–5 years are more likely than the same cold periods, and the periods without rain with the duration of 3–5 years are more likely than the rainy periods. This indicates that the cyclical increase in the mean annual air temperature and the annual precipitation decrease in the southern part of the East European Plain. The calculations of climatic periods alternation results set the maximum probability for hot-cold periods 0.275 ($t = 2$) and for wet-dry periods 0,242 ($t = 3$).
3. The results of neuro modeling determine that the accuracy of the generated artificial neural networks for the climatic parameters prediction were as follows: the average annual air temperature made 84%, the amounts of precipitation made 78%. A stable unfavorable trend is planned for climatic factors change till 2020: the increase of the average temperature by 0.6 °C and the decrease of annual precipitation amount by 4 mm.
4. A retrospective analysis and the results of climate change forecast confirmed the high likelihood of further manifestations for abnormal climate changes in the southern steppe of the East European Plain. The presented approaches to the multi-dimensional treatment of meteorological data may be used for study and accurate prediction of the main climate parameters in other regions, to determine the multi-year cyclical patterns of environmental change in the global climate change conditions, as well as for the development of a space-time adaptive environmental management programs.

5. Conflict of Interest

The authors confirm that this article content has no conflicts of interest.

6. Acknowledgments

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