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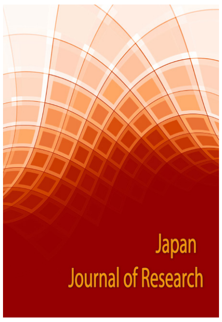

Dynamic Stochastic Model of Atmospheric Drought Forecast in Uzbekistan

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Abstract

The article considers a predictive model of atmospheric dryness with a one-month lead time, developed at the Scientific Research Hydrometeorological Institute. The model is based on a dynamic stochastic approach to constructing a regression predictive equation. From the set of existing methods for constructing regression equations, a method based on the characteristic roots (eigenvalues) of a correlation matrix, including a column of the predicted variable and predictor columns (extended matrix) is applied.

The predicted variable is the standardized drought index SPI, and the predictors are the average monthly precipitation for the 3 months preceding the forecast month, the average monthly value of variations in solar activity (Wolf numbers) and the average monthly value of the Southern Oscillation index for the month preceding the forecast.

The predictors were selected on the basis of mutual correlation and applied time series analyses between the aridity index SPI and the indicated heliogeophysical values. The performed estimates of the studied dependence of the aridity index SPI on the state of solar activity, the influence of El Niño (La Niña) and precipitation preceding the forecast date showed their high correlation.

Estimates of the accuracy of the SPI forecast with a monthly advance lead time for the territory of Uzbekistan, performed on an independent sample, were quite high, which was the basis for the introduction of this model into the operational work of the hydrometeorological service of Uzbekistan (Uzhydromet).

Introduction

Atmospheric drought is a natural phenomenon with an abnormally low amount of precipitation and elevated temperatures [1], manifested in various geographical areas of the globe, with an extremely uneven spatial distribution. The urgency of the forecast of atmospheric drought is determined by the damage to the economy, significant social consequences, often escalating into a humanitarian disaster.

When developing a predictive model based on the construction of a regression equation, the main factors of its correctness are, firstly, the stability of the resulting equation when switching to data on an independent sample and the optimal choice of predictors. The predictors included in the regression equation are determined primarily from physical considerations responsible for the dynamics of the predictor, supported by a statistical analysis of the conditioning of the latter by a selected set of predictors.

It is important to choose a method for constructing a regression equation, in particular, when constructing multiple regression, which often gives low results on an independent sample.

In this paper, the construction of a regression model is based on the use of the

method of characteristic roots (eigenvalues) of the inverse correlation matrix of the predictor and predictors [2,3].

The data used and the rationale for the selected predictors

The data used in this work were observational data on precipitation on the meteorological network of the Uzhydromet for the observation period 1966-2023 for 12 regional centers and the city of Tashkent. Based on these data, the average monthly precipitation values for each month of the year were obtained, according to which the standardized index of aridity SPI [4], recommended by the World Meteorological Organization (WMO), was calculated as one of the most informative indices of the state of aridity (humidity) of the atmosphere. The specified index in the developed model acts as a predictor. During the same period, the monthly average values of the Wolf numbers were entered into the generated database, which are

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freely available on the website (http://www.kosmofizika.Ru/spravka/spots.htm) characterizing the dynamics of variations in solar activity and the average values of the Southern Oscillation index SOI, which are also freely available on the website https://www.ncdc. noaa.gov/teleconnections/enso/indicators/soi/ data.csv. The latter in the model, along with precipitation for the 3 months preceding the forecast period, are used as predictors, but with a monthly delay, i.e. the month preceding the forecast month is selected from the database.

The Wolf Numbers W characterize the states of solar activity

$$W = k\,(f + 10g), \qquad (1)$$

where f - is the number of observed spots, g- is the number of observed groups of spots, and k - is the normalization coefficient.

In [5], a significant dependence of droughts on the position of the year in the 11-year cycle of solar activity was established. However, the influence of variations in solar activity in various geographical areas of the planet on the state of the atmosphere, in particular, its aridity (moisture content) is different, up to a change in the sign of influence. Thus, the spring-summer droughts in the European territory according to the catalog of N. G. Kamenkova [6] rely on the ascending branch of solar activity, while the droughts in Central Asia, taken from the catalog of A.S. Utesheva [7,8] are grouped on the descending branch of solar activity. For Central Asia, the percentage of droughts on the ascending branch relative to the descending one is 1:11. This dependence is clearly illustrated in Figure 1 by the cross-correlation function and the causality function [9,10] between the Wolf numbers and the SPI index as functions of time shift. Within the framework of the choice of predictors in the construction of the regression equation, the most important is the fact that the causality function in the entire range of time shifts remains in the region of normal causality, i.e. unambiguously variations in solar activity cause variations in dryness in the specified area, and negative values of the cross-correlation function in the region of time shifts ± 3 years are confirmed. Feedback is expected between variations in solar activity and the processes of formation of droughts.

The SOI Southern Oscillation index: The climate system is characterized by large-scale self-oscillatory processes, such as Southern oscillation (redistribution of air masses in the low latitudes of the Southern Hemisphere between the Indian and Pacific Oceans) and ocean fluctuations – El Niño (warm phase) and La Niña (cold phase).

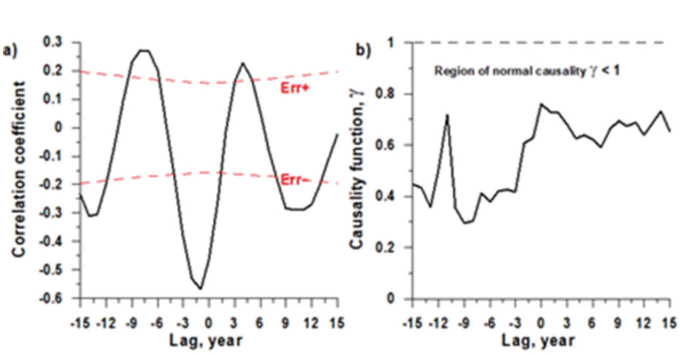

Figure 1. *Cross-correlation function (a) and causality function (b) between Wolf Numbers W and the aridity index SPI, as a function of time shift.*

The quantitative characteristic of the ENUC is the SOI Southern Oscillation Index, introduced by G. Walker in 1924 [11]. The southern oscillation is an atmospheric component of air currents and represents fluctuations in air pressure in the surface layer of the atmosphere between the waters of the eastern and western Pacific Oceans. The CPI index is calculated based on the difference in surface air pressure in the area of Tahiti (French Polynesia) and Darwin (Australia) and is determined by the ratios (2) [11]:

$$SOI = \frac{P_T - P_D}{\acute{o}_{TD}},\ P_T = \frac{P_T^{sur} - \overline{P}_T}{\acute{o}_T},\ P_D = \frac{P_D^{sur} - \overline{P}_D}{\acute{o}_D},$$

$$\acute{o}_T = \sqrt{\frac{\sum_{i=1}^{N}\left(P_{Ti}^{sur} - \overline{P}_T\right)^2}{N}},\qquad \acute{o}_D = \sqrt{\frac{\sum_{i=1}^{N}\left(P_{Di}^{sir} - \overline{P}_D\right)^2}{N}}, \qquad (2)$$

$$\acute{o}_{TD} = \sqrt{\frac{\sum_{i=1}^{N}\left(P_{T_i}^{sur} - P_{D_i}^{sur}\right)^2}{N}}.$$

In (2) P_T^{sur} surface pressure at Tahiti point, P_D^{sur} at Darwin point, $\overline{P}_T$. $\overline{P}_D$ average surface pressures over the base period in the corresponding points. Figure 2 shows the cross-correlation functions between SPI and SOI for each month of the year in Uzbekistan. The influence of ENUK on atmospheric processes that stimulate aridity in the territory of Uzbekistan varies: to a lesser extent, this influence manifests itself, starting from June to September, and the greatest – in the cold period of the year.

Methods of analysis and construction of the regression equation

Construction of a predictive regression equation based on characteristic roots. The regression procedure on characteristic roots was developed by R. Webster, G. Hans and R. Mason [Webster, Guns, Mason] and independently of them by D. Hawkins [1]. This method is described in detail in [2,3,12,]. Following, for example, [12], we present an algorithm that implements the regression construction procedure on characteristic roots (eigenvalues).

The time series of predictors *Fi(tj), i=1, 2, ..., 5, j=1, 2, ..., N* (precipitation for the three months preceding the forecast, the index of the Southern oscillation and the Wolf number) and the predictor *Zi(tj)* (index SPI) are standardized:

$$\sigma_{iF} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(F_i(t_j) - \overline{F_i}\right)^2},\ X_i(t_j) = \frac{F_i(t_j) - \overline{F_i}}{{}_{iF}},$$

$$Y_i(t_j) = \frac{Z_i(t_j) - \overline{Z_i}}{\acute{o}_{iZ}},\ \sigma_{iZ} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(Z_i(t_j) - \overline{Z_i}\right)^2} \qquad (3)$$

where - mean square deviations; the top line is averaging. An extended matrix A of size Nx (i+1) is constructed:

$$A = (Y, X) = \begin{bmatrix} Y_{11} & X_{11} & X_{11} & \dots X_{i1} \\ Y_{11} & X_{11} & X_{11} & \dots X_{i2} \\ \vdots & \vdots & \vdots & \vdots\ \vdots \\ Y_{1N} & X_{1N} & X_{2N} & \dots X_{iN} \end{bmatrix} \qquad (4)$$

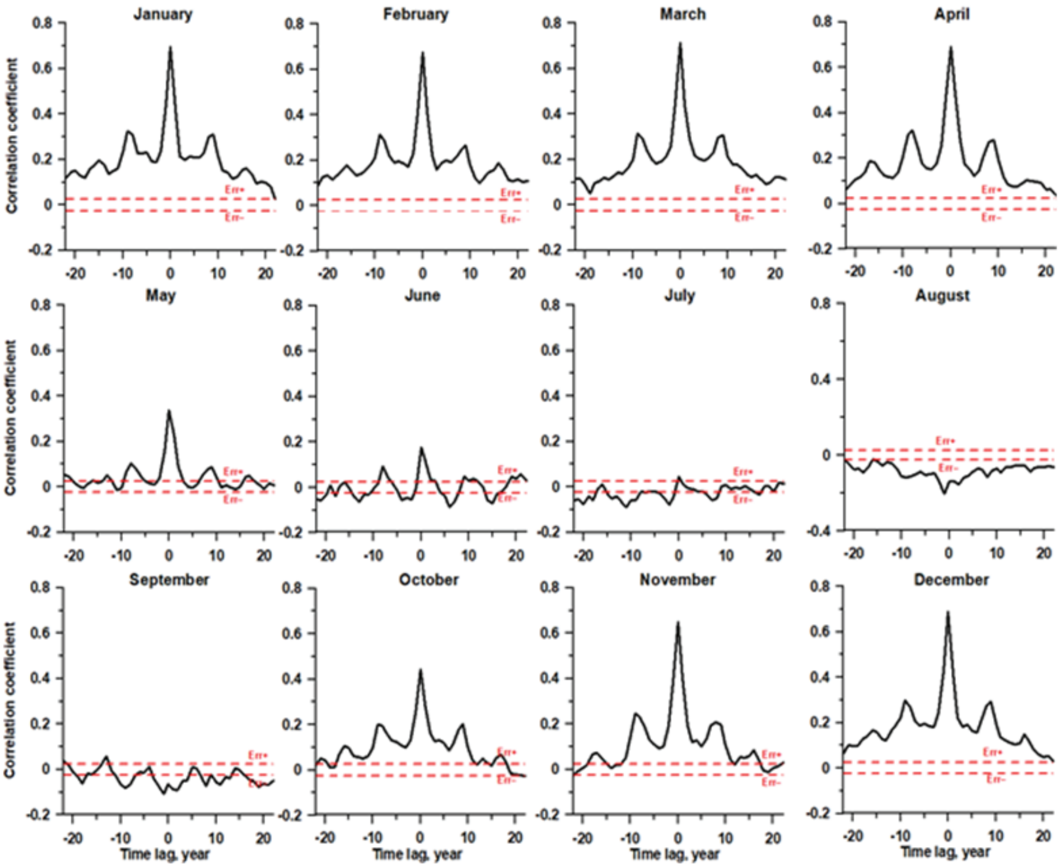

Figure 2. *Correlation functions between drought index SPI and Southern Oscillation Index SOI as a function of time shift.*

$$R = \begin{bmatrix} 1 & R_{11} & R_{21} & \ldots R_{i1} \\ & 1 & R_{22} & \ldots R_{i2} \\ & & \vdots & \vdots \quad \vdots \\ & & & \ldots \;\; 1 \end{bmatrix} \qquad (5)$$

The next step is to calculate the eigenvalues and eigenvectors of the correlation matrix (5) and arrange the eigenvectors in accordance with the decreasing magnitude of the eigenvalues. Estimates of the regression coefficients aj are based on the formula

$$a_j = -\frac{c\sum_{m=1}^{k} v_{om} v_{jm}}{\ddot{e}_m}, \quad j = 1, 2, \ldots, k \qquad (6)$$

where v_{om} is the 1st eigenvector, v_m are the subsequent eigenvectors arranged in descending order of eigenvalues λ_m, and c is determined from the expression

$$c = \left(\sum_{m=1}^{k} \left(v_{om}^2 \right) / \lambda_m \right)^{-1} \times \sigma_z .$$

Numerical experiments

To conduct numerical experiments for forecasting atmospheric dryness for the month ahead, a database was used, the components of which are predictors: average monthly precipitation, the Southern oscillation index, Wolf numbers and the predictor - calculated values of the SPI aridity index. The training sample period for all predictors and predictor was 50 years, and the independent (examination) sample was 10 years. The forecast based on the model was calculated for 12 regional centers and Tashkent city.

As quantitative estimates of the accuracy of the forecast, the following are taken:

- standard error

$$\acute{o}_{for} = \frac{1}{N} \sum_{i=1}^{N} (SPI_{akt} - SPI_{for})^2 \qquad (7)$$

- maximum absolute error:

$$\ddot{A}_{max} = max \left| SPI_{akt} - SPI_{for} \right| \qquad (8)$$

- match by sign

$$\rho = \frac{n_+ - n_-}{n} \qquad (9)$$

In (7), (8) SPI_{akt} -is the actual value of the aridity index; SPI_{for} - is the prognostic value of the aridity index. In (9) n+ - the number of SPI values with matched signs, n_ - with non–matched signs, n - is the total number of cases.

Summary table presents the results of a quantitative assessment of the accuracy of the forecast with a one-month advance of the average monthly value of the aridity index SPI, as an average of 13 points according to formulas (7) - (9).

Summary table: Average scores on all points

Forecast month	Estimated parameter			
	Δ_{max}	ρ	R	σпр
January	1,152	0,886	0,771	0,383
February	1,085	0,954	0,818	0,246
March	0,741	0,980	0,881	0,154
April	1,588	0,913	0,787	0,376
May	2,091	0,812	0,703	0,556
June	2,038	0,692	0,664	0,579
July	1,768	0,793	0,661	0,471
August	1,399	0,791	0,736	0,367
September	1,414	0,771	0,736	0,413
October	2,184	0,665	0,629	0,644
November	1,803	0,852	0,742	0,543
December	1,859	0,874	0,654	0,585
Average	1,593	0,832	0,732	0,443

As follows from the estimates presented in the table, on average, the level of justification of the forecast for the parameter of atmospheric aridity with a month's advance is more than 80%, which is approaching the level of justification of short-term forecasts, which is currently the highest.

Conclusions

In general, it can be stated that the presented estimates of the model, taking into account the monthly forecast lead time, can be considered quite high, which made it possible to introduce this predictive model of atmospheric aridity into the operational work of the hydrometeorological service of Uzbekistan..

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