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Stochastic Generator of Monthly Precipitation and Monthly Average Temperature

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Abstract—A method is proposed for simulating the monthly precipitation and monthly average temperature of air near the earth's surface. The proposed algorithm is based on the method of inverse functions. The climatic parameters used in simulations were derived from the UEA/CRU database. The method was applied to simulate time series of monthly precipitation and monthly average temperatures of air over a dry land territory with a spatial resolution of $0.5 \times 0.5°$ in latitude and longitude. The time series of the climatic parameters obtained with the proposed stochastic generator appear statistically adequate to actual data series for any time interval in months and years.

INTRODUCTION

In analyzing and studying the environment, many problems require long time series of climatic parameters. Actual time series of required climatic characteristics appear often insufficiently long for obtaining reliable estimates of occurrence of an event under study. In these conditions, one is forced to simulate time series of climatic parameters starting from data obtained for these parameters from observations. These simulations are performed with the use of stochastic weather models called also weather generators.

Weather generators are most frequently used for analyzing characteristics of the hydrologic cycle of the atmosphere and the underlying land surface [1–3], for modeling the dynamics of vegetation [4, 5], and for forecasting the reaction of plants on variations in agroclimatic conditions [6–8]. Weather generators are also used in a number of modern studies of the dynamics of regional climate and in estimating possible regional climate changes in the near future [9–11], forecasting variations caused in the trends of climatic characteristics under climate change [12, 13], and estimating the risks in projects of carbon sink [14, 15].

At the moment, several tens of weather generators are designed. They allow simulating the time series of different climatic parameters from observed data. Stochastic weather models are briefly reviewed in papers [7, 11, 16]. Two basic approaches can be recognized among the conceptual grounds of these generators. One of them regards weather processes as first-order Markov random chains characterized by two states, the first state corresponding to humid days, i.e., the days with measurable precipitation, and the second state corresponding to dry days, i.e., the days without precipitation and the days with insignificant precipitation. Conditional probabilities of state-to-state conversion are determined from local weather data, and climatic parameters (such as precipitation amount, temperature, and solar radiation) are simulated as functions of the resulting state. This approach forms the basis for weather generators such as, for example, WGEN [17] and Met&Roll [7]. The second method of simulating is based on the so-called serial approach [18]. The essence of this method lies in the fact that data of long-term observations are used to simulate the lengths of continuous sequences (series) of humid and dry days following one after another during a year. Then, depending on the length of every series, one simulates climatic parameters. This method forms the basis for the LARS-WG weather generator [19, 20].

Stochastic weather models are usually local models and require calibration against observed data for each new geographic location.

In weather generators, the precipitation amount is frequently simulated using a gamma distribution [16, 21–24]. The properties of this distribution and procedures of determination of its parameters from experimental data have been discussed many times in the literature [24–26]. Many research workers simulated the amount of precipitation in a region under study using other special distributions known in probability theory, such as the log-normal distribution, the first-kind Pearson distribution, and the mixed exponential distribution [16, 18, 21, 26]. The simulation of air temperatures near the earth's surface usually assumes that these temperatures are governed by a normal (Gaussian) distribution [18, 22]. A number of research workers reported the air temperature distributions (obtained from meteorological data for the territories being considered) that differ from a Gaussian distribution (see, for example, [21, 27]). Consequently, the widely used hypothesis that the

distribution functions of precipitation and temperature are independent of the geographic location of the territory under study is a fairly controversial assumption.

The task of this paper is to construct such a method for simulating monthly precipitation and monthly average temperatures of air that would be applicable to any region.

METHOD OF SIMULATING

In this investigation, we use climatic data (monthly average temperatures of air and monthly precipitation) derived from the UEA/CRU database developed and distributed by the Division of Climatic Research, University of Eastern England [28]. This database contains long-term climatic data covering the territory with the $0.5 \times 0.5°$ spatial spacing in latitude and longitude for the period 1901–1995. In this paper, we consider only the data concerning the dry land covered with vegetation.

The solution of our problem starts with the determination of distributions of monthly precipitation and average monthly temperatures in every spatial cell for every month in a year. With this goal in mind, we construct the so-called statistical series of climatic parameters from their time series.

We denote the minimum and maximum values of a climatic parameter in the ith month ($i = 1, 2, \ldots, 12$) by $x^i_{\min}$ and $x^i_{\max}$ and the number of times at which this parameter was measured during this month by N^i. We divide the range of this parameter into n segments of equal length $[x^i_{\min}, x^i_{\max}] = \bigcup_{j=1}^{n} [x^i_j, x^i_{j+1}]$ and count the number of times m^i_j at which the measured value of this parameter falls within each interval of this division. From m^i_j, we derive the frequencies of falling within the corresponding intervals,

$$p^i_j = m^i_j / N^i.$$

The collection of segments $[x^i_j, x^i_{j+1}]$ and the corresponding frequencies p^i_j determine the statistical series of a particular climatic parameter for the ith month.

For a specified spatial cell, the climatic parameter is said to have low-probability values in segments

$$[x^i_1 = x^i_{\min}, x^i_k] = \bigcup_{j=1}^{k-1} [x^i_j, x^i_{j+1}] \quad \text{and}$$

$$[x^i_t, x^i_n = x^i_{\max}] = \bigcup_{j=t}^{n-1} [x^i_j, x^i_{j+1}],$$

if the frequency p^i_j does not exceed $1/N^i$ for any subsegment $[x^i_j, x^i_{j+1}]$ of these segments. The climatic characteristic values for the ith month are considered to be regular if these values fall within the segment $[x^i_k, x^i_t] = \bigcup_{j=k}^{t-1} [x^i_j, x^i_{j+1}]$.

Available data are insufficient for determining an appropriate distribution of low-probability values of the climatic parameters of interest. As the simplest mathematical hypothesis, we assume that these values of temperature and precipitation are distributed uniformly.

For regular values, the distribution functions of climatic characteristics of interest can be determined from the statistical series obtained for the ith month. Without loss in generality, we assume that the equality $\sum_{j=1}^{n} p^i_j = 1$ holds for regular values of both precipitation and temperatures in spatial resolution cells under consideration. For the climatic parameters of interest, we specify empirical distribution functions at the limiting points of the segments $[x^i_j, x^i_{j+1}]$, which appear in the statistical series of these parameters, in the following manner:

$$F(x^i_1) = 0,$$
$$F(x^i_j) = a^i_j, \quad j = \overline{2, n-1},$$
$$F(x^i_n) = 1,$$

where $a^i_j = \sum_{k=0}^{i} p^i_k$. Joining the adjacent points by straight lines, we obtain the empirical distribution function. Thus, we use the distribution functions specified by the formula

$$F(x) = \begin{cases} 0, & x < x_1, \\ p_j \dfrac{x - x_{j-1}}{x_j - x_{j-1}} + a_{j-1}, & x_{j-1} \le x < x_j, \quad j = \overline{2, n}, \\ 1, & x \ge x_n. \end{cases} \quad (1)$$

As a consequence, our task reduces to simulating random quantities governed by the distribution functions of the form (1). For this purpose, we use the method of inverse functions [29]. Essentially, the method is as follows.

Consider a random quantity X distributed according to the law

$$F(x) = P\{X < x\}. \quad (2)$$

Determine the distribution function $F'(y)$ of the random quantity $Y = F(X)$, where the function $F(X)$ is specified by relation (2). By the definition of the distribution function, the values of the random quantity Y lie in the interval (0,1) and

$$F'(y) = P\{Y < y\} = P\{F(X) < F(x)\}.$$

Table 1. (1) Actual and (2) simulated monthly precipitation (mm) for the dry land territory (an estimate from a sample of 95 values)

Range of latitudes	Data	Month											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
75–70°N	1	21.2	21.3	22.2	18.1	18.2	31.7	38.0	42.2	35.3	28.5	27.1	22.7
	2	20.8	20.9	21.8	17.6	17.7	31.3	37.7	41.9	34.9	28.1	26.7	22.3
70–60°N	1	24.1	20.3	20.9	21.6	28.1	43.6	55.6	56.8	45.3	37.1	31.4	26.2
	2	23.9	20.1	20.7	21.3	27.8	43.4	55.5	56.7	45.2	36.9	31.2	25.9
60–50°N	1	33.8	26.2	28.8	32.2	44.4	63.7	78.5	73.4	59.3	49.8	44.2	38.5
	2	33.6	26.0	28.6	32.0	44.3	63.7	78.4	73.2	59.2	49.7	44.0	38.4
50–40°N	1	33.9	29.3	34.3	39.7	49.9	59.2	62.2	56.9	46.4	41.4	40.3	38.2
	2	33.7	29.2	34.1	39.6	49.8	59.2	62.2	56.8	46.3	41.4	40.2	38.1
40–30°N	1	38.3	37.8	45.1	44.4	44.8	46.6	58.9	53.8	42.5	33.8	33.7	37.6
	2	38.2	37.7	45.0	44.4	44.8	45.5	58.9	53.7	42.5	33.8	33.7	37.5
30–20°N	1	14.1	17.0	22.2	32.5	50.1	81.9	102.6	97.2	67.8	33.6	16.2	12.7
	2	14.0	16.9	22.2	32.4	50.0	81.7	102.4	97.1	67.8	33.7	16.2	12.7
20–10°N	1	12.4	9.9	12.6	23.8	58.8	102.8	142.7	159.6	121.7	71.8	34.9	18.7
	2	12.3	9.8	12.5	23.8	58.9	102.6	142.6	159.4	121.5	71.8	34.9	18.6
10–0°N	1	69.2	67.8	102.4	150.5	195.0	190.3	188.3	188.3	178.9	167.9	117.7	82.5
	2	69.2	67.8	102.5	150.5	194.8	190.3	188.1	188.2	178.8	167.9	117.7	82.5
0–10°S	1	208.5	207.5	243.8	223.9	159.2	98.8	81.2	79.1	100.7	140.0	172.4	193.5
	2	208.2	207.3	243.5	223.8	159.0	98.9	81.1	79.0	100.7	139.9	172.3	193.3
10–20°S	1	208.6	189.2	170.9	79.3	31.9	17.2	14.6	15.1	28.2	67.0	117.9	183.1
	2	208.8	189.1	171.0	79.5	32.1	17.3	14.5	15.0	28.1	67.0	118.0	183.0
20–30°S	1	87.6	80.7	67.5	40.2	32.8	25.8	21.7	19.2	25.8	43.4	53.7	73.9
	2	88.3	80.9	67.8	40.5	33.0	25.9	21.9	19.3	25.8	43.4	53.8	74.0
30–40°S	1	48.0	48.7	53.5	45.3	51.0	50.8	49.7	46.3	44.3	50.5	47.4	48.0
	2	48.2	49.1	53.6	45.6	51.0	51.0	49.8	46.4	44.3	50.6	47.4	48.1
40–50°S	1	55.2	47.6	61.6	69.5	92.1	87.1	85.1	81.7	67.8	64.2	57.1	60.0
	2	55.3	47.6	61.6	69.9	92.0	87.1	85.3	81.7	67.7	64.0	57.2	59.9
50–60°S	1	46.1	41.2	51.3	49.8	46.5	42.5	41.3	43.7	33.6	33.7	38.0	42.2
	2	46.2	41.2	51.7	49.6	46.7	42.5	41.2	43.9	33.7	33.5	37.9	42.1

Because $F(X)$ is a monotonically increasing function, the condition $F(X) < F(x)$ is equivalent to the condition $X < x$, so that

$$P\{F(X) < F(x)\} = P\{X < x\} = F(x) = y,$$

and $0 \le y \le 1$, which means that the random quantity Y is uniformly distributed on the interval (0,1). Thus, any random quantity can be transformed to a random quantity uniformly distributed on the interval (0,1).

The opposite is also true: if Y is the random quantity uniformly distributed on the interval (0,1) and $F(x)$ is the distribution function of some random quantity X, then the random quantity X can be obtained from the random quantity Y using the formula

$$X = F^{-1}(Y), \qquad (3)$$

where F^{-1} is the function inverse to the function F. Indeed, for the monotonically increasing function $F(x)$, the inequality $F^{-1}(Y) < x$ is equivalent to the inequality $Y < F(x)$. As a consequence, we have

$$P(X < x) = P\{F^{-1}(Y) < x\} = P\{Y < F(x)\} = F(x).$$

Thus, we have the procedure for transforming a sequence of random numbers with a uniform distribution law in the interval (0,1) into a sequence of random numbers with a given distribution function $F(x)$. This transformation assumes that one chooses a random number y out of the set of random numbers uniformly distributed in the interval (0,1) and then solves the equation

$$F(x) = y$$

Table 2. (1) Actual and (2) simulated monthly average temperatures of air (°C) for the dry land territory (an estimate from a sample of 95 values)

Range of latitudes	Data	Month											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
75–70°N	1	–31.5	–31.3	–28.0	–19.9	–9.1	0.6	5.2	2.6	–4.1	–14.4	–25.4	–29.5
	2	–31.5	–31.3	–28.0	–19.9	–9.1	0.6	5.2	2.5	–4.1	–14.5	–25.4	–29.5
70–60°N	1	–26.5	–24.9	–19.3	–10.3	–0.6	7.6	11.4	9.1	3.0	–6.7	–18.3	–24.4
	2	–26.5	–24.9	–19.3	–10.3	–0.6	7.6	11.4	9.1	2.9	–6.8	–18.3	–24.5
60–50°N	1	–18.3	–16.3	–9.6	–0.1	7.5	13.1	16.0	14.3	8.8	1.2	–8.4	–15.7
	2	–18.3	–16.3	–9.7	–0.2	7.5	13.1	16.0	14.3	8.8	1.2	–8.4	–15.8
50–40°N	1	–10.3	–8.4	–2.1	6.2	12.6	17.3	20.2	19.0	13.8	6.9	–1.3	–7.8
	2	–10.4	–8.5	–2.1	6.2	12.6	17.3	20.1	19.0	13.8	6.9	–1.4	–7.9
40–30°N	1	–0.3	1.7	6.1	11.4	16.2	20.6	23.2	22.5	18.6	12.7	6.2	1.3
	2	–0.4	1.7	6.1	11.4	16.2	20.5	23.1	22.5	18.6	12.7	6.2	1.3
30–20°N	1	12.8	14.6	18.3	22.4	26.1	28.4	28.7	28.3	26.5	22.9	17.9	13.9
	2	12.7	14.6	18.3	22.4	26.1	28.3	28.7	28.2	26.5	22.9	17.9	13.9
20–10°N	1	21.5	23.2	26.0	28.5	29.9	29.6	28.3	27.6	27.7	27.0	24.4	22.0
	2	21.4	23.2	25.9	28.5	29.8	29.6	28.3	27.6	27.7	27.0	24.4	22.0
10–0°N	1	24.7	25.6	26.3	26.3	25.7	24.9	24.3	24.4	24.9	25.1	25.0	24.6
	2	24.7	25.6	26.2	26.2	25.7	24.9	24.3	24.4	24.8	25.1	25.0	24.6
0–10°S	1	25.0	25.1	25.2	25.2	24.9	24.2	23.9	24.4	25.1	25.4	25.4	25.2
	2	25.0	25.1	25.2	25.2	24.9	24.2	23.8	24.4	25.0	25.4	25.4	25.1
10–20°S	1	24.5	24.5	24.3	23.3	21.5	19.6	19.3	20.8	23.0	24.6	24.9	24.7
	2	24.5	24.5	24.2	23.3	21.4	19.5	19.2	20.8	23.0	24.5	24.9	24.7
20–30°S	1	26.0	25.4	23.8	20.6	16.9	14.1	13.6	15.5	18.5	21.4	23.7	25.4
	2	26.0	25.4	23.8	20.6	16.9	14.1	13.6	15.5	18.5	21.4	23.7	25.3
30–40°S	1	22.4	21.9	19.6	16.0	12.5	9.8	9.1	10.4	12.8	15.6	18.6	21.0
	2	22.3	21.8	19.6	15.9	12.5	9.7	9.1	10.3	12.8	15.6	18.6	21.0
40–50°S	1	14.4	14.1	12.2	9.2	6.0	3.5	3.1	4.2	6.3	8.9	11.1	13.2
	2	14.4	14.1	12.2	9.2	6.0	3.5	3.1	4.2	6.3	8.9	11.1	13.2
50–60°S	1	9.7	9.4	8.1	6.0	3.1	1.3	0.8	1.8	3.5	5.8	7.3	8.9
	2	9.7	9.4	8.1	5.9	3.1	1.3	0.8	1.7	3.5	5.7	7.3	8.9

for x. The solution is a random number of the set of random numbers with the distribution function $F(x)$.

Thus, in accordance with formula (3), the sequence of random numbers with the distribution function (1) can be derived from the sequence of random numbers uniformly distributed in the interval (0,1) by the formula

$$x = F^{-1}(y) = (x_j - x_{j-1})(y - a_{j-1})/p_j + x_{j-1},$$

if $a_{j-1} \le y < a_j$ and $a_j = \sum_{k=0}^{j} p_k$.

RESULTS

The proposed stochastic generator of monthly precipitation and monthly average temperatures of air does not relate to any particular site of investigation and is applicable to any region under study.

Values obtained with this generator for monthly precipitation and monthly average temperatures of air agree well with actual data for these climatic parameters. Tables 1 and 2 list actual and simulated values of monthly precipitation and monthly average temperatures calculated for a dry land territory. From the data of these tables, it follows that the differences between simulated values and empirical data are within the measurement error.

The difference between actual and calculated values of the climatic parameters can be estimated from the curves given in Figs. 1 and 2. Figures 1a and 1b show curves of monthly precipitation for January and July along the meridian 20° E, where the dry land territory

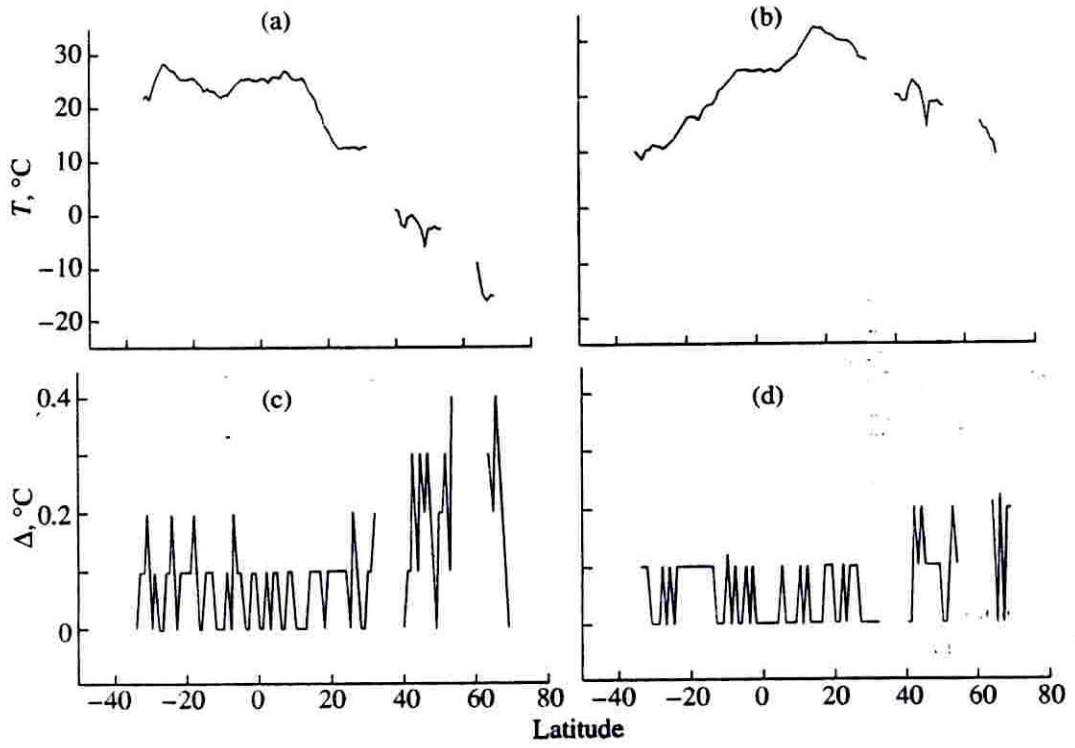


Fig. 1. Comparison of actual and simulated precipitation for the dry land territory along the meridian 20° E: (a) average precipitation of January (P) for the period 1901–1995, (b) average precipitation of July (P) for the period 1901–1995, (c) absolute deviation (Δ) of average precipitation of January (during the period 1901–1995) from average precipitation of January estimated from a sample of 95 generated values, and (d) absolute deviation (Δ) of average precipitation of July (during the period 1901–1995) from average precipitation of July estimated from a sample of 95 generated values.

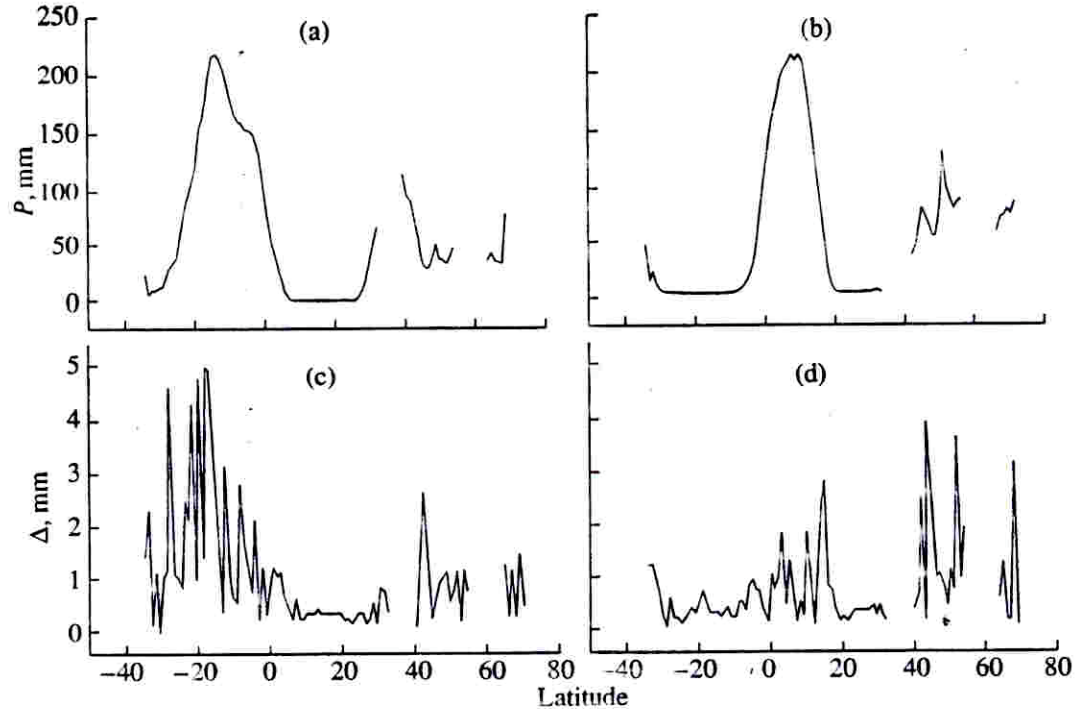


Fig. 2. Comparison of actual and simulated temperatures for the dry land territory along the meridian 20° E: (a) average temperature of January (T) for the period 1901–1995, (b) average temperature of July (T) for the period 1901–1995, (c) absolute deviation (Δ) of average temperature of January (during the period 1901–1995) from average temperature of January estimated from a sample of 95 generated values, and (d) absolute deviation (Δ) of average temperature of July (during the period 1901–1995) from average temperature of July estimated from a sample of 95 generated values.

Table 3. Statistical characteristics of (1) actual and (2) simulated distributions of annual precipitation P (mm) and annual average temperatures of air T (°C)

Range of latitudes	Data	Average value		Lower quartile		Median		Upper quartile	
		P	T	P	T	P	T	P	T
75–70°N	1	326.4	−15.4	310.2	−16.0	330.9	−15.4	342.0	−14.7
	2	321.8	−15.4	307.5	−15.9	320.4	−15.4	334.6	−14.9
70–60°N	1	411.1	−8.3	379.2	−9.1	410.7	−8.3	439.6	−7.5
	2	408.7	−8.4	379.5	−8.9	406.3	−8.4	435.5	−7.8
60–50°N	1	572.8	−0.6	528.1	−1.3	571.9	−0.6	614.8	0.1
	2	571.1	−0.7	527.8	−1.2	568.2	−0.7	611.4	−0.1
50–40°N	1	531.8	5.5	480.6	4.9	528.3	5.5	578.8	6.1
	2	530.5	5.5	481.9	5.0	526.6	5.5	574.8	5.9
40–30°N	1	517.2	11.7	460.7	11.2	512.4	11.7	566.6	12.1
	2	516.6	11.7	461.1	11.4	510.4	11.7	565.6	12.0
30–20°N	1	547.8	21.7	495.1	21.4	541.9	21.7	594.4	22.0
	2	547.1	21.7	494.6	21.5	540.1	21.7	592.7	21.9
20–10°N	1	769.8	26.3	709.6	26.0	765.2	26.3	824.6	26.6
	2	768.6	26.3	708.6	26.1	760.9	26.3	821.6	26.5
10–0°N	1	1698.9	25.1	1606.1	24.9	1697.3	25.1	1779.8	25.4
	2	1698.4	25.1	1609.5	25.0	1691.4	25.1	1781.0	25.3
0–10°S	1	1908.5	24.9	1809.3	24.6	1914.2	24.9	1995.4	25.2
	2	1907.2	24.9	1813.2	24.8	1900.7	24.9	1994.5	25.0
10–20°S	1	1122.9	22.9	1034.7	22.5	1120.4	22.9	1199.0	23.3
	2	1123.4	22.9	1033.3	22.7	1114.1	22.9	1203.5	23.1
20–30°S	1	572.3	20.4	496.7	20.0	560.8	20.4	634.2	20.9
	2	574.6	20.4	501.8	20.2	562.9	20.4	635.1	20.6
30–40°S	1	583.4	15.8	507.7	15.4	575.1	15.8	647.3	16.2
	2	585.1	15.8	514.6	15.5	575.5	15.8	646.2	16.0
40–50°S	1	829.1	8.9	760.6	8.5	817.4	8.9	884.8	9.2
	2	829.3	8.8	767.5	8.6	822.2	8.8	885.2	9.1
50–60°S	1	510.0	5.5	448.8	5.2	496.9	5.4	559.7	5.8
	2	510.1	5.4	461.0	5.2	503.7	5.4	552.7	5.6

encompasses a wide bioclimatic range. Figures 1c and 1d show curves for the absolute differences between simulated results and actual data for these months. It follows that the differences between calculated and actual monthly average precipitation are insignificant: the maximum discrepancy (2–5 mm) occurs in regions with heavy monthly precipitation (100–240 mm). Figure 2 shows similar curves for monthly average temperatures of air. As follows from these curves, the discrepancy between simulated and actual values of this climatic characteristic is below 0.4°C.

The degree of agreement between the distributions of actual and calculated climatic characteristics can be estimated from the distributions of annual precipitation and annual average temperatures of air obtained with the use of monthly values of the corresponding quantities. Table 3 lists the following statistical characteristics of these distributions for dry land territories at different latitudes: average values, medians, and lower and upper quartiles. These numerical characteristics provide an idea of the arrangement and scatter of the values of the parameters under investigation. From the data of Table 3, it follows that the distributions of simulated and actual values of the climatic parameters analyzed here are in good agreement.

DISCUSSION

The above method of simulating monthly precipitation and monthly average temperatures of air near the earth's surface offers a possibility of generating the time series of these climatic parameters that are statis-

tically adequate to the initial data. Because the implementation of the proposed method assumes the use of a climatic data archive for constructing empirical distribution functions of these parameters for every spatial cell, the generated time series of climatic characteristics appear strongly dependent on the initial data set. As a consequence, the simulated results will change if one use another archive for the initial actual data, and the degree of this change will depend on the differences between the data of new and old archives.

The proposed method of simulating monthly precipitation and monthly average temperatures of air near the earth's surface is independent of a specific spatial resolution of the meteorological data archive. This fact suggests that our method will be adequate for generating the time series of the given climatic characteristics by using initial data with another spatial resolution.

An analysis of statistical characteristics such as average values, medians, and lower and upper quartiles for the distributions of annual precipitation and annual average temperatures of air that are obtained from the monthly values of the corresponding quantities shows that the distributions of simulated and actual values of the climatic parameters under investigation are in good agreement. From this analysis, it follows that our method can be used to reconstruct, to a certain approximation, the regular annual behavior of temperatures and precipitation.

CONCLUSIONS

The proposed stochastic generator of monthly precipitation and monthly average temperatures of air is a priori divorced from a particular distribution type predefined for these quantities. Monthly precipitation and monthly average temperatures of air obtained with this method of simulation agree well with actual data for these climatic parameters.

The statistical analysis of simulated results have shown that the assumption on the uniform distribution of low-probability values of the climatic parameters of interest is acceptable in the problem under consideration. Nevertheless, we believe that improving generated series of the climatic characteristics of interest requires further investigations in this field.

The estimates given in the paper provide evidence in favor of reliability of the proposed method of simulating and advisability of its use for creating simulated time series of climatic parameters from available observational data.

It should be noted that we derived the empirical distribution functions from data obtained during 1901–1995, and it is precisely for this period that these functions are representative of the climate variability. The empirical distribution functions of the climatic parameters for certain particular periods, such as cooling off during the 1960s and present-day warming up, are of great interest for a number of investigations. Our method has no hard restrictions on the duration of the time period of initial data; for this reason it can be used in the above-mentioned investigations.

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