ISSN 1068-3739, Russian Meteorology and Hydrology, 2018, Vol. 43, No. 6, pp. 397–403. Allerton Press, Inc., 2018.
Original Russian Text E.M. Gusev O.N. Nasonova, E.E. Kovalev, G.V. Aizel', 2018, published in Meteorologiya i Gidrologiya, 2018, No. 6, pp. 77–86.

Possible Climate Change Impact on River Runoff in the Different Regions of the Globe

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Received June 30, 2017; in final form, August 1, 2017

Abstract—The possibility of assessing changes in river runoff till 2100 for a number of large river basins of the world for a wide range of natural conditions is investigated. The assessment is based on the SWAP (Soil Water–Atmosphere–Plants) model using meteorological data as inputs which were simulated with different general atmosphere–ocean circulation models in accordance with the RCP climate change scenarios. The possible climatic changes in annual runoff for some rivers by the end of the 21st century are compared with the natural interannual variability of river runoff caused by weather noise.

DOI: 10.3103/S1068373918060079

Keywords: River runoff, climate change, SWAP model, ISI-MIP, global databases

INTRODUCTION

Nowadays, many studies deal with the assessment of possible climate change impact on inland water resources using different models. However, such estimates are mostly provided on the global and continental scales. As to the modeling of changes in hydrological regime on the regional scale (for example, on the scale of a river basin), such studies are largely fragmentary, are based on different climate scenarios and on the results of simulations with various climate and hydrological models. As a result, the obtained scenarios of possible changes in hydrological characteristics sometimes cannot be summarized and systematized and do not always include the uncertainty assessment. In view of this, the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) was organized in 2013 [12]. One of its goals was to combine efforts of the community of developers of hydrological models in order to generalize the obtained projections of global climate change impact on water resources on various spatial scales, in particular, on the river basin scale. The present research was performed in the framework of ISI-MIP2; its objective was to investigate the possible variation in river runoff till 2100 for 11 large river basins characterized by a wide range of natural conditions. Such studies were also carried out by other ISI-MIP2 participants using different hydrological models [5, 9]. Unlike the above papers, the present study utilizes the SWAP (Soil Water–Atmosphere–Plants) model simulating interaction between the land surface and atmosphere which has been developed before by the authors of the present paper [1]. The authors have enough experience in solving the problems of the scenario-based prediction of water balance components, in particular, of river runoff for river basins (for example, see [2]). Besides, the authors tried to summarize the obtained results in the given paper based on the construction of the regression dependence of river runoff variations on the changes in climatic predictors (surface air temperature and precipitation) and to compare the scale of climatic changes in river runoff with its natural variability caused by so called weather noise [6, 8].

DATA AND METHODS

SWAP model. The SWAP physical and mathematical model of the land surface–atmosphere interaction developed in the Water Problems Institute of Russian Academy of Sciences describes the processes of heat and moisture exchange in the soil–plants/snow cover–atmosphere system. The latest version of the model considers the following processes: the interception of liquid and solid precipitation by vegetation;

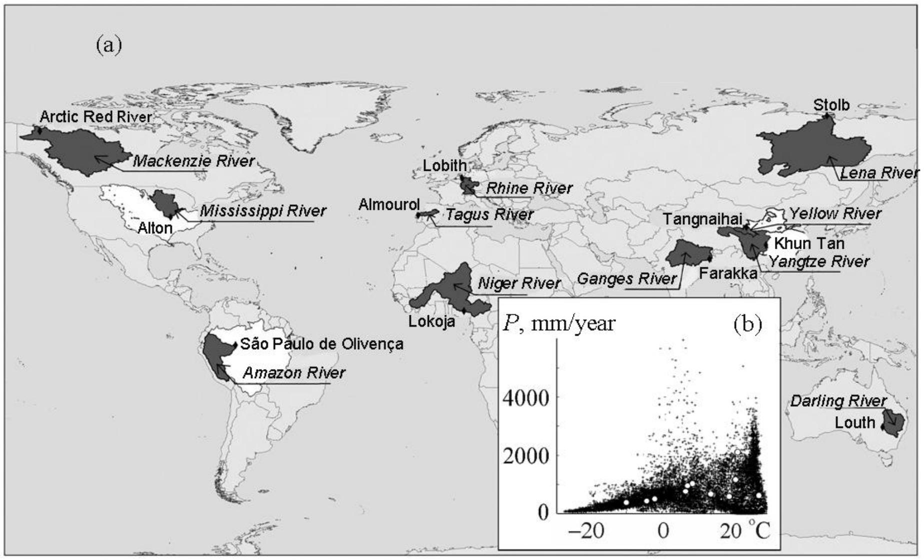

Fig. 1. The location of the analyzed river basins (a) on the globe and (b) in the phase space of the climatic values of surface air temperature T and precipitation P that were averaged over the area of the respective object. The small crosses in figure b mark the position (in the phase space) of the values of T and P belonging to the territory of land cells of the spatial global grid with the resolution of 1 ; the circles mark the investigated river basins.

the evaporation, melting, and freezing of intercepted precipitation including the meltwater refreezing; the formation of snow cover under the forest canopy and in the open areas; the formation of surface and groundwater runoff; the infiltration of water into the soil; the formation of water balance in the aeration zone including transpiration, evaporation from the soil, water exchange with underlying layers, and soil moisture dynamics; groundwater level variations; the formation of heat balance and temperature regime of the above system; the freezing and melting of soil.

In hydrological applications, the kinematic wave equation is used for modeling runoff within the model grid cell. A large-scale river basin is split on the surface to a number of grid cells connected by the river network. Within each cell the heat and water regimes are simulated regardless of the other cells. The values of runoff from the basin grid cells are used as input information for the next model component: the component of runoff transformation in the river network.

Output variables for the SWAP model are the several tens of characteristics of thermal and water regimes of the analyzed river basin. However, in accordance with the goal stated and due to the limited volume of the paper, the present study considers only the most interesting characteristic for hydrologists: the river runoff.

The detailed description of SWAP and its verification are provided in [1].

Analyzed river basins and their schematization. The objects of the present study are 11 large river basins located on the different continents of the globe in different natural conditions: the Rhine and Tagus in Europe; the Ganges, Lena, Upper Yellow, and Upper Yangtze in Asia; the Niger in Africa; the Mackenzie and Upper Mississippi in North America; the Upper Amazon in South America; the Darling in Australia (Fig. 1a). The use of only upper reaches of such rivers as the Yellow, Yangtze, Mississippi, and Amazon for the analysis is caused by the fact that these parts of river basins are least subjected to anthropogenic impacts which considerably affect the river runoff and do not require additional information related to the runoff control. The basic characteristics of the selected river basins are presented in Table 1 [7, 9].

In the present study, the basins were schematized as the set of regular grid cells with the spatial resolution of 0.5 along the latitude and longitude that are connected by the river network. The number of grid cells for each basin is given in Table 1.

Figure 1b presents two sets of spatial land objects in the phase space of two climatic characteristics (average long-term values of average annual temperature and annual total precipitation). The first set is the set of all land cells (except for Antarctica), and the second one is the set of 11 selected river basins. The aver-

Table 1. The characteristics of the investigated river basins

River	Runoff station	Latitude	Longitude	S, km^2	N	T, C	P	R	R/P
							mm/year		
Lena	Stolb	72.37 N	126.80 E	2460000	1668	–10.2	384	201	0.52
Upper Amazon	So Paulo de Olivensa	3.45 S	68.75 W	990781	330	21.7	2122	1459	0.69
Mackenzie	Arctic Red River	67.46 N	133.74 W	1660000	1128	–4.3	435	171	0.39
Upper Yangtze	Khun Tan	29.61 N	106.60 E	804859	325	6.8	768	389	0.51
Ganges	Farakka	25.00 N	87.92 E	835000	340	21.1	1173	471	0.40
Upper Yellow	Tangnaihai	35.50 N	100.15 E	121000	51	–2.0	506	169	0.33
Niger	Lokoja	7.80 N	6.77 E	2074171	678	27.7	625	77	0.12
Rhine	Lobith	51.84 N	6.11 E	160800	83	8.7	1038	457	0.44
Upper Missis-sippi	Alton	38.89 N	90.18 W	444185	198	7.3	967	257	0.27
Tagus	Almourol	39.47 N	8.37 W	674900	35	14.0	671	152	0.23
Darling	Louth	30.53 S	145.11 E	489300	180	19.2	590	8	0.01

Note: S is the basin area; N is the number of grid cells; the area-averaged climatic characteristics of the basin (from 1971 to 2000): T is surface air temperature; P is precipitation; R is river runoff; R/P is the runoff coefficient [7, 9].

age long-term values of air temperature and annual total precipitation for the mentioned objects are the area-averaged characteristics determined from the global meteorological database Water and Global Change (WATCH) [13]. It follows from Fig. 1b that river basins form the sample of land objects which more or less representatively indicate (at least in terms of climate characteristics) the specific features of most of the land on the globe.

SWAP information support. Surface meteorological data (on precipitation, air temperature, air humidity, intensity of long- and short-wave radiation fluxes, wind speed, and air pressure) are needed to specify upper boundary conditions for the SWAP model; the parameters of land surface (the characteristics of soil, vegetation, terrain, etc.) are specified; hydrological characteristics are also needed to calibrate and verify the model.

To calibrate and verify the model, the daily values of meteorological data for the period of 1969–2001 were taken from the above WATCH global database which is based on the hybridization of ERA-40 reanalysis data with monthly values of surface measurements from the databases of GPCC (Global Precipitation Climatology Center) and University of East Anglia CRU (Climatic Research Unit) (including data on air temperature, number of days with precipitation, cloudiness, and precipitation).

For prognostic calculations, daily meteorological data for the period of 2006–2099 were used whichw ere obtained from five general atmosphere–ocean circulation models (GCMs): Had-GEM2-ES, IPSL-CM5A, MIROC-ESM-CHEM, GFDL-ESM2M, and NorESM1-M [9] based on four representative concentration pathways (RCPs) [10], RCP2.6, RCP4.5, RCP6.0, and RCP8.5, which were used to prepare the IPCC Fifth Assessment Report. The numbers in the acronyms of scenarios correspond to the increase in the values of incoming radiation in 2100 which is caused by the increase in greenhouse gas emissions to the atmosphere as compared to the preindustrial period. High values correspond to more aggressive anthropogenic scenarios caused by the high greenhouse gas emission to the atmosphere and by poor emission control measures. Besides, the present study used the values of meteorological parameters simulated with GCMs for the historical period (1962–2005).

To improve the quality of the further hydrological calculations during ISI-MIP2 [12], the post-processing correction was provided for the values of meteorological parameters obtained with the above five GCMs in order to reduce possible calculation biases. The correction was based on corresponding data from WATCH for the historical (base) period P0 (1962–2005) which was used to optimize the most important parameters of the basins.

The land surface parameters for each grid cell of the basins were obtained using the ECOCLIMAP ecosystem database [3] by the method described in [7].

Data on river runoff for the calibration and verification of the model were provided by the ISI-MIP2 organizers.

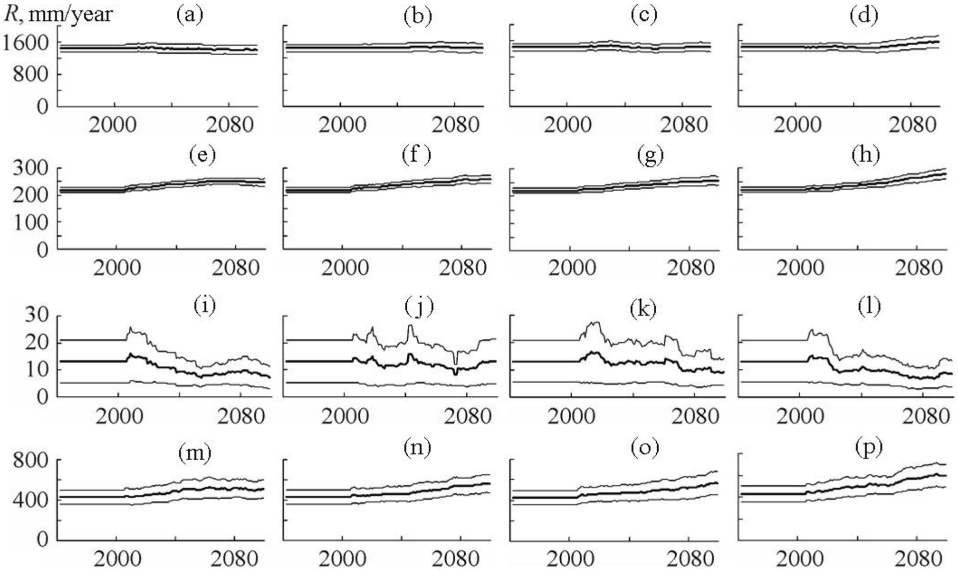

Fig. 2. The dynamics of climatic variations in runoff in the 21st century for four selected river basins calculated with the SWAP model using meteorological data as inputs which were simulated with different general atmosphere–ocean circulation models in accordance to the RCP climate change scenarios. The thick line is the results of multimodel climatic variations (averaged for all GCMs), the thin lines are the error of the mean value of runoff estimated by the scatter of results obtained for different GCMs. (a–d) the Upper Amazon; (e–h) Mackenzie River; (i–l) Darling River; (m–p) Ganges River; scenarios: (a, e, i, m) RCP2.6; (b, f, j, n) RCP4.5; (c, g, k, o) RCP6.0; (d, h, l, p) RCP8.5.

Model calibration and verification. To improve the quality of hydrological calculations, the automatic calibration was provided for the most important model parameters based on the SCE-UA global optimization algorithm (Shuffle Complex Evolution) [4], with application of the additional condition that the runoff calculation bias must not exceed 5%. The standard deviation of calculated monthly runoff values from the measured ones was used as a target function. The calibration was carried out (as possible) for the 8-year period based on the monthly values of measured runoff. The more detailed description of the calibration procedure, in particular, of the selection of parameters to be calibrated can be found in [7].

The adequacy test for the obtained optimized values of parameters was performed for the period from 1970 till 2001 and revealed a quite satisfactory agreement between the calculated and measured dynamics of runoff for the selected rivers [7].

RESULTS AND DISCUSSION

The runoff for the above 11 rivers was calculated using the SWAP model based on the GCM-simulated values of meteorological parameters for two main periods: the historical period P0 (1962–2005) and the projection period (2006–2099) which, in turn, was split to three parts for the analysis: P1 (2006–2035), P2 (2036–2065), and P3 (2066–2099). The river runoff for the projection period was calculated for the four above RCP climate scenarios.

Due to the limited volume of the paper, Figure 2 presents only a part of the results of runoff variation estimation for the 21st century, namely, the dynamics of annual values of river runoff (averaged using the simulation results and the meteorological forcing computed with five GCMs) for four basins and all four climate scenarios. The mean values for the period are given for P0, and the time-averaged values obtained by the moving average method with the averaging period of 30 years are provided for the next (prognostic) years, i.e., the results in Fig. 2 represent the dynamics of climatic runoff. Besides, Figure 2 also demonstrated the runoff estimation uncertainty caused by the scatter of simulation results for different GCMs and computed as a root-mean-square error of the ensemble mean. The projections of the change in climatic runoff by the end of the 21st century for all the analyzed rivers and for all climate scenarios are presented in Table 2.

Table 2. Statistical characteristics indicating runoff changes for the analyzed rivers in the end of the 21st century (period P3) as compared with the historical period (P0) under different RCP climate change scenarios

Parameter	Amazon	Ganges	Darling	Lena	Mackenzie	Mississippi	Niger	Rhine	Tagus	Yellow	Yangtze
					RCP2.6						
R	–32	82	–6	35	28	21	1	46	14	4	–3
$_{\text{mod}}$	85	93	5	12	11	32	13	27	43	22	22
SNR	0.40	0.45	0.28	2.01	1.36	0.17	0.13	0.05	0.39	0.14	0.01
					RCP4.5						
R	–6	133	0	49	40	19	–3	16	–24	4	5
$_{\text{mod}}$	63	97	16	11	10	34	10	31	42	17	27
SNR	0.51	0.46	0.10	2.17	1.47	0.16	0.18	0.04	0.41	0.18	0.01
					RCP6.0						
R	8	139	–4	62	37	11	–4	13	–29	–5	–10
$_{\text{mod}}$	79	120	8	15	13	32	10	29	36	16	20
SNR	0.40	0.38	0.24	1.65	1.16	0.17	0.17	0.04	0.44	0.19	0.01
					RCP8.5						
R	127	172	–5	99	59	21	–7	5	–65	–12	1
$_{\text{mod}}$	78	85	8	17	16	31	9	38	23	20	30
SNR	0.41	0.51	0.20	1.48	0.93	0.17	0.18	0.03	0.69	0.16	0.01

Note: R is the averaged value of runoff variation (mm/year) calculated using different GCMs; $_{\text{mod}}$ is the standard deviation of runoff variations obtained using different GCMs from R, mm/year.

The analysis of the results demonstrated that, as a rule, more aggressive RCP scenarios lead to significant (both positive and negative) variations in river runoff in the selected basins. As to the relative error of climatic runoff (equal to the absolute value of the error divided by the mean value of runoff), it was maximum for the Darling and Tagus rivers. It should be noted that, according to [7], the basins of these rivers are also characterized by the highest natural uncertainty of runoff caused by weather noise. On the contrary, for the Lena and Mackenzie rivers, the above error is minimum. This also corresponds to the lowest values of natural uncertainty of runoff for these rivers, because they are characterized by a more regular pattern of intraannual runoff dynamics [7]. Evidently, the basins with the highest amplitude of weather noise are characterized by the widest range of values of meteorological parameters calculated using different GCMs. In turn, this widens the range of river runoff values calculated based on them.

As regards the values of runoff variation R, they differ (both in value and sign) for the basins located in the different regions of the globe, because variations in climate characteristics differ (Table 2). The authors tried to generalize the results of assessment for average long-term runoff variations using basin-averaged variations in temperature T (here, T is temperature, K) and precipitation P as predictors. The main energy characteristic affecting runoff variation is a change rather in the related incoming long-wave radiation which is proportional to T^4 than in temperature; therefore, the variation in this parameter was utilized as a predictor. Thus, the values of P and $T^4 \sim T^3 \quad T$ were taken as predictors. For convenience, the last predictor was utilized in the form of the following variable (let us call it the reduced temperature variation)

$$T^* \quad (T/T_0)^3 \quad T \tag{1}$$

where $T_0 = 273.15$ K.

Then variations in the average long-term values of annual runoff R computed with the SWAP model for the periods P1, P2, and P3 (averaged over all RCP scenarios and all GCMs) were approximated with the parabolic function of variables T^* (K) and P (mm/year):

$$R(\quad T^*,\quad P)\quad a\quad T^*\quad b\quad P\quad c(\quad T^*)^2\quad d(\quad P)^2\quad e\quad P\quad T^* \tag{2}$$

where a, b, c, d, and e are empirical parameters.

In the case of optimum values of the empirical coefficients in the right-hand side of (2) ($a = -8.21$, $b = 0.57$, $c = 1.7$, $d = 0.0023$, $e = -0.065$), the coefficient of correlation between the values of R calculated using SWAP and equation (2) is equal to 0.9. The standard deviation of values of R calculated with SWAP from the values of R computed using (2) is equal to 14 mm/year. The comparison of this value with the standard deviations for runoff calculated using different GCMs and presented in Table 2 allows concluding that, as a first guess, the climate change impact on long-term annual runoff variations can be assessed based on empirical equation (2).

It is interesting to determine to what extent climate-induced variations in average long-term annual runoff are comparable with its natural (caused by weather noise) interannual variability. For this purpose, the signal-to-noise relation *SNR* can be used. It is applied in climatology to estimate the significance of any anthropogenic signal against a background of natural variability of meteorological parameters (for example, see [11]). In the present study, *SNR* was computed in the following way:

$$SNR\quad \frac{|\quad R_3|}{Un} \tag{3}$$

where R_3 is runoff variation for a corresponding river (averaged for all GCMs) for the period P3 as compared with the base period P0; $Un = (R_{0.975} - R_{0.025})$ is the measure of the natural variability of annual runoff, where $R_{0.975}$ and $R_{0.025}$ are the quantiles with 97.5% and 2.5% probability of annual runoff for the period P3 (mm/year) calculated assuming that annual runoff is lognormally distributed [7, 8]. The characteristic *Un* is a range within which the value of annual runoff can be with the 95% probability under more or less stationary climate conditions.

The results of *SNR* computation are presented in Table 2. They indicate that, as a rule (except for the runoff of the northern rivers Mackenzie and Lena), the climate-related runoff variations (in the absolute value) for the selected rivers by the end of the 21st century obtained using the RCP family scenarios are below (and often much below) the natural interannual variability of river runoff caused by weather noise.

CONCLUSIONS

The possibility of assessing river runoff variations till 2100 for the large river basins of the globe characterized by a wide range of natural conditions is demonstrated. The assessment is based on the SWAP model of land surface–atmosphere interaction and uses meteorological data as inputs which were simulated with different general atmosphere–ocean circulation models in accordance to the RCP climate change scenarios.

The possibility of estimating variations in climatic annual runoff based on the empirical equation is shown. The predictors in the equation are variations in basin-averaged surface air temperature and precipitation amount.

It is demonstrated that, as a rule, climate-caused runoff variations (in the absolute value) for the analyzed rivers (except for the northern rivers) in the end of the 21st century will be smaller than the natural interannual variability of runoff caused by weather noise.

ACKNOWLEDGMENTS

The research was supported by the Russian Science Foundation (grant 16-17-10039), the section “Model calibration and verification” was supported by the Ministry of Science and Education of the Russian Federation (project No. 14.B25.31.0026).

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