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Variations of the Present-Day Annual and Seasonal Runoff in the Far East and Siberia with the Use of Regional Hydrological and Global Climate Models

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Abstract—A method of spatial calibration and verification of regional numerical physically based models of river runoff formation, incorporating runoff formation processes in the main river channel and its tributaries, was used to obtain a statistical estimate of the quality of river runoff calculation by conventional and alternative criteria focused on runoff reproduction in different phases of water regime and the characteristics of its variations. The analysis of the simulation quality of the annual and mean monthly river runoff (average runoff, standard deviation, and the coefficient of variation) at the near-mouth gages over the historical period with boundary conditions represented by data of global climate models showed the results to be satisfactory. This allows the proposed combination of climate and hydrological models to be used to study physically based regional variations of water regime under different physiographic and climatic conditions in the examined river basins with flood runoff regime (the Amur R.) and the predominant snowmelt runoff during spring flood (the Lena R.).

Keywords: runoff formation model, global climate model, the Amur and Lena rivers

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INTRODUCTION

The problems considered in this study are of importance in the examination of the vulnerability of natural and socioeconomic systems to variations in the renewable water resources in large river basins. The available estimates of river runoff variations are mostly based on the results of calculations by General Circulation Models (GCMs) or Global Hydrological Models (GHMs), which utilize simplified parameterizations of the processes involved in land hydrological cycle, but ignore the regional features of river runoff formation. Such studies are mostly focused on the calculation of evaporation, while the runoff is calculated as the difference between precipitation and evaporation. The hydrological blocks of climate models, as well as global hydrological models, are commonly not verified against the available observation data, resulting in a greater uncertainty of the estimates of the future changes.

Since recently the possible changes in water regime caused by climate changes have been evaluated with the use of regional physically based distributed runoff formation models with boundary conditions specified as scenarios of the future hydrometeorological impacts on river catchment, calculated with the use of general circulation models of the atmosphere and ocean [5, 9]. The application of physically based models of runoff formation, verified by the reproduction of water regime characteristics of the period for which observation data are available, reduces the uncertainty in the obtained estimates of the hydrological effects of climate changes. The values of most parameters of the hydrological models have been taken from global databases on the land surface, and they have some physical meaning, which, in combination with a physical description of hydrological processes, enables the solution of extrapolation problems with a high spatial resolution. This will improve the efficiency of measures aimed to adapt the strategy of effective and environmentally safe management of water resources to climate changes in the regions under study. This article gives the analysis of the reproduction of long-term variations of water regime characteristics in large rivers of Siberia and the Far East over the observation period with boundary conditions in hydrological models specified by the data of ensemble calculations of GCMs, i.e., at the regional scale. The hydrological models used in the study are regional runoff formation models (RHMs) for the Amur and Lena basins, which evaluate the daily discharges in the main channel and in tributaries with a statistical estimate of calculation efficiency over long-term calibration and verification periods in different phases of river water regime.

MATERIALS AND METHODS

The study was focused on the Amur and Lena basins, large rivers in Siberia and the Far East. The total catchment area of the Amur R. basin is 1855 thous. km^2 (46% of this area belongs to the territories of China and Mongolia). The Amur Basin lies between 42° and 56° N, and 108° and 142° E. The river belongs to the Pacific Ocean Basin. The major tributaries are the Zeya and Bureya rivers from the left and the Sungari and Ussuri rivers from the right. The Amur Basin lies in moderate climate zone with distinct monsoon character of atmospheric circulation and cyclonic activity. The mean annual discharge at the mouth is 11300 m^3/s. Several large reservoirs were constructed in the Amur Basin to reduce the flood hazard, including Zeya and Bureya reservoirs in RF territory and the Fengman, Baishan, Lianhua, and Nierzi reservoirs in PRC territory.

The Lena R. basin ranks eighth in the world in terms of its area (2460 thous. km^2) and extends from 52° to 73° N and from 103° to 142° E. The Lena R. belongs to the Arctic Ocean Basin and accounts for about 15% of the total freshwater discharge into it. The basin lies in the zone of cold sharp continental climate. Its water regime shows a high spring flood, summer and autumn freshets, and low water level in winter. The major tributaries are the Aldan, Vilyui, Vitim, and Olekma rivers. The mean annual discharge in the Lena R. is 15400 m^3/s. The large Vilyui Reservoir is in operation in the Lena R. Basin.

The models were developed based on the ECOMAG software (ECOlogical Model for Applied Geophysics) [7, 8] with a daily time step and a spatial resolution of half the size of the computation grid (elementary catchment). Such characteristics are enough to describe the spatial distribution in the catchment of the processes of snow cover formation and melting, soil freezing and thawing, vertical heat and mass transport in frozen and unfrozen soil, evapotranspiration, surface and subsurface runoff, groundwater flow, water flow in the river system with the effect of reservoirs taken into account. The major portion of the spatially distributed model parameters are measurable characteristics of the river basin, which have been taken from databases of the relief and the characteristics of soils and landscapes. Some parameters were calibrated against discharge data at different gages in the main river channel and tributaries.

The model of runoff formation in the Amur Basin is described in detail in [3, 4]. The model of the Lena R. was developed on the basis of global land surface databases and, unlike the earlier version of the model, which used Russian databases [2], this model has fuller meteorological information support. In addition, the models were adapted to enable the specification of boundary conditions in the form of time series of mean daily air temperature, relative air humidity, and precipitation, based on various types of meteorological data (both taken from weather stations and calculated by climate models).

The river network and basins were schematized as a hierarchy of elementary partial catchments (model units) based on HYDRO1k digital elevation model with a spatial resolution of 1 km. The total number of the chosen elementary river catchments in the Amur Basin was 1947, and the mean catchment area was 950 km^2; the respective values for the Lena Basin were 664 and 3700 km^2. The model parameters, distributed over the basin area, were evaluated using global databases: Harmonized World Soil Database and the landscape database Global Land Cover Characterization. The percent concentrations of sand, clay, gravel, and organic matter for each soil type were substituted into a pedotransfer function to evaluate the following hydrophysical characteristics (input model parameters): bulk density, porosity, field capacity, wilting point, and hydraulic conductivity [3]. Some model parameters were taken from the global base of landscape types: degree-day melting factor, soil moisture evaporation coefficient, and soil freezing factor. As the result, each elementary catchment in the examined river basin was described by a set of soil types, landscapes, and relief altitudinal distribution, which determine model parameters.

The base of meteorological source data, required for specifying boundary conditions in the models, was derived from the data of RIHMI-WDC and the courtesy of colleagues from PRC. The base includes time series of mean daily values of the surface temperature and relative air humidity, and daily precipitation, measured at 232 weather stations in the Amur Basin (of which 169 are in the Russian part of the basin) and 203 weather stations in the Lena Basin.

A base of hydrological characteristics had been created for model calibration, including data on daily discharges, taken from the annual data on the regime and resources of continental surface water at different gages in the Amur and Lena basins, as well as the operational data of Federal Water Resources Agency on discharges from the Zeya, Bureya, and Vilyui reservoirs. Because of the lack of data on discharges from reservoirs in the Sungari Basin in PRC territory, the reservoirs were described as lakes by a linear capacity model. Similarly, the model takes into account the discharge from Lake Khanka in the Amur Basin. The prepared input data were used to calibrate the model in terms of various parameters, governing among which were the coefficient in the formula for calculating soil moisture evaporation, degree-day melting factor, horizontal and vertical hydraulic conductivity of soil, critical temperature for determining the phase of precipitation, and snow cover melting. The calibration procedure was organized such as to preserve the proportions between the absolute values of each spatially distributed parameter for the soil types identified in the catchment and landscape characteristics, i.e., to eliminate systematic errors in the calculation.

The climate models reproduce the daily fields of weather characteristics with considerable errors, resulting in the instability of estimates of river water regime variations by hydrological models with these data as inputs. More reliable estimates can be obtained by averaging the calculated runoff values over long time intervals (a month or a year). Given below are the results of comparison of the mean monthly and annual values of discharges, calculated by runoff formation models and observed in the Amur and Lena basins.

The agreement between the simulated and observed mean monthly runoff volumes was evaluated using the Nash–Sutcliffe criterion (NSE), which is in wide use in hydrological studies; modified Kling–Gupta efficiency (KGE); and the relative error of mean annual runoff calculation (BIAS).

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{f(i)} - Q_{s(i)}\right)^2}{\sum_{i=1}^{n}\left(Q_{f(i)} - \overline{Q_f}\right)^2}, \quad (1)$$

$$\mathrm{KGE} = 1 - \sqrt{(r-1)^2 + \left(\frac{\overline{Q_s}}{\overline{Q_f}} - 1\right)^2 + \left(\frac{\sigma_s/\overline{Q_s}}{\sigma_f/\overline{Q_f}} - 1\right)^2}, \quad (2)$$

$$\mathrm{BIAS} = \frac{\overline{Q_s} - \overline{Q_f}}{\overline{Q_f}} \times 100\%, \quad (3)$$

where $Q_{f(i)}$ and $Q_{s(i)}$are the observed and simulated values of discharge in the ith month, $\overline{Q}$ is the mean value of the observed discharges over period $I = 1, 2, 3...n$, σ_f and σ_s are the root-mean-square deviations of the observed and simulated discharges.

The use of various quality criteria for model reproduction of the characteristics of observed river water regime ensures more objective estimation of their potential in experiments with climate models. In the process of manual calibration, the values of BIAS criterion, averaged over the gages considered in the study, were minimized, and the values of modified NSE and KGE criteria were maximized. In the process of averaging, larger weights were assigned to gages with larger catchment areas. The quality of calculations is the better, the closer the values of NSE and KGE to unit, and the values of BIAS, to zero. Basing on the simulation quality estimates proposed in [6] as functions of a combination of the values of NSE, KGE, and BIAS, we assumed that runoff hydrograph simulation is good at $0.7 \le \mathrm{NSE} \le 1$, $0.7 \le \mathrm{KGE} \le 1$, and $|\mathrm{BIAS}| \le 10\%$ and satisfactory at $0.5 \le \mathrm{NSE} < 0.7$, $0.5 \le \mathrm{KGE} < 0.7$, and $10\% < |\mathrm{BIAS}| \le 15\%$. Considering the future application of the developed models to estimating the hydrological effects of climate changes, additional estimates of the efficiency of river runoff simulation were made using criteria focused on variation characteristics (root-mean-square deviation, the coefficient of variation) of river runoff characteristics. With this in view, BIAS_σ and BIAS_{CV} were calculated for annual runoff volumes.

In the numerical experiments with the developed hydrological models, to reduce the uncertainties and to improve the accuracy and space and time resolution of climate calculations in the basins under consideration, data on the surface fields of meteorological characteristics were involved. These characteristics had been calculated by the ensemble of GCMs CMIP5 based on the results of Inter-Sectoral Impact Model Intercomparison Project Phase 2b (ISI–MIP2b) over the historical period (up to 2005) at the observed concentrations of greenhouse gases and aerosols. The data were prepared by the transformation of the primary calculated mean daily values of air temperature and humidity and precipitation in four climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM) over the historical period to data of global meteorological reanalysis EWEMBI, developed by Potsdam Institute for Climate Impact Research (Germany) by reanalysis ERA–Interim [1] in the nodes of regular grid 0.5° × 0.5°.

To obtain reliable estimates of climate changes requires averaging meteorological characteristics over a long time. Now, the World Meteorological Organization recommends thirty-year period to be used in such estimates. In the Amur and Lena basins, the basic historical period was taken to be the end of the XX century (1970–1999).

RESULTS AND DISCUSSION

Calibration and Validation of Hydrological Models

Model parameters for the Amur Basin were calibrated for period 1994–2003 at 10 gages with catchment areas from 0.02 to 1.8 million km^2; such calibration for the Lena Basin was made at seven gages with catchment areas from 0.44 to 2.5 million km^2 (Fig. 1; Table 1). The models were verified at the same gages with independent measurement data over period 2004–2013.

The values of the quality criteria NSE, KGE, and BIAS show that the simulation results of the mean monthly and annual discharges for eight gages in the Amur Basin and four gages in the Lena Basin are good or satisfactory. However, the results for the Khor, Selemdzha, and Vilyui rivers and the gages of Krestovsky and Tabaga on the Lena R. are unsatisfactory in terms of BIAS criterion; those for the Khor and Vilyui rivers and the Krestovsky gage are unsatisfactory by BIAS_σ criterion, and that for the Vilyui R. is unsatisfactory by criterion BIAS_{CV}. The deterioration of simulation quality in low-water period, as typical of winter, can be due to the poor accuracy in the evalua-

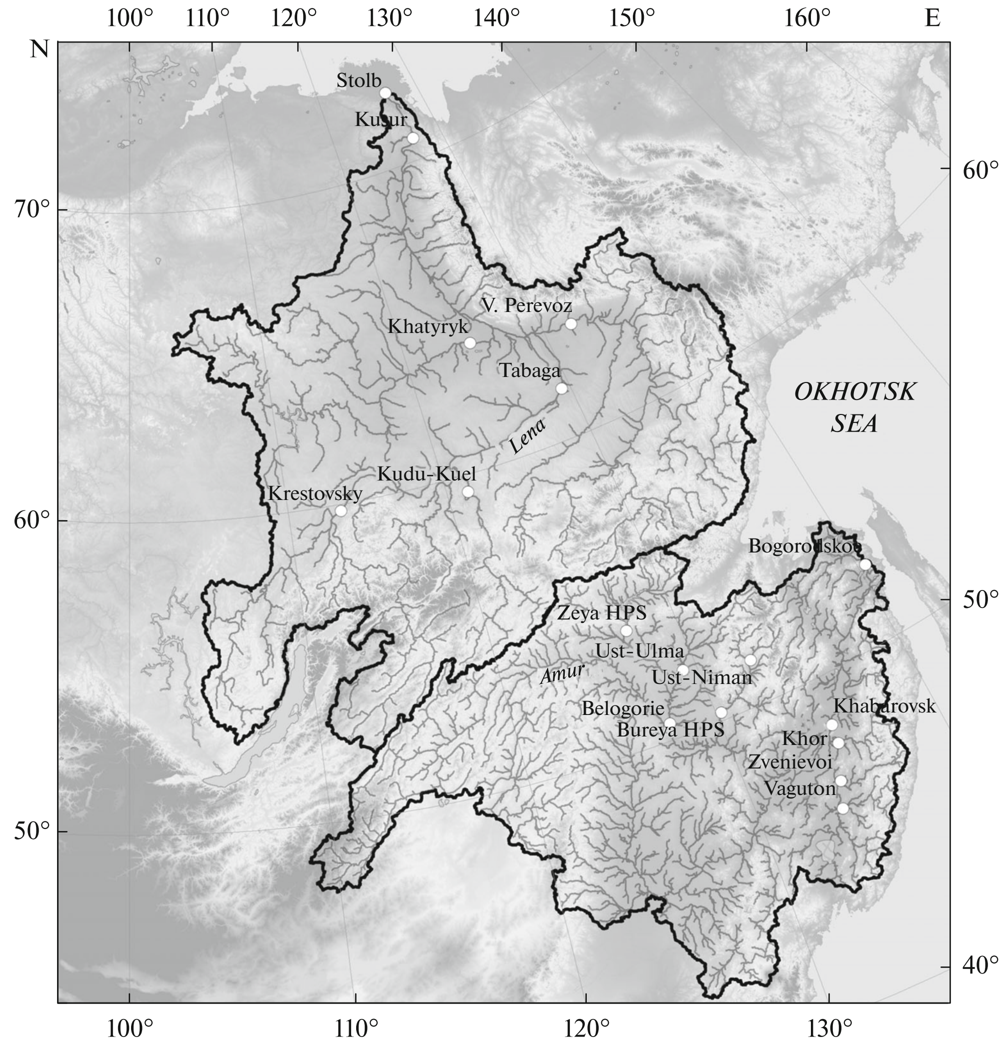

Fig. 1. Layout of gages the data from which were used to calibrate runoff formation models for the Amur and Lena basins.

tion of observed discharges in the under-ice period. The systematic errors in the calculation of the average long-term runoff and its variations for some gages with catchment areas smaller than those for other gages, are likely due to the neglect of the local features of river runoff formation typical of these rivers.

The area-weighted averages of the statistical criteria values obtained for the examined rivers (Table 1) suggest the conclusion that the accuracy of runoff hydrograph estimates for rivers in the Amur and Lena basins over the observation period by data of surface meteorological measurements is high. In addition, the quality criteria showed low sensitivity at the transition from the calibration to verification period, suggesting the robustness of the models, i.e., the invariance of their structure and parameters with respect to the inputs used.

The obtained satisfactory results in river runoff simulation and the robustness of the models over the observation period suggest the conclusion that the developed runoff formation models are applicable to the evaluation of possible hydrological effects of climate changes in the examined river basins. We emphasize that the models were adjusted not for individual basins of main-river tributaries, but for the entire basin with a single set of parameters. The physiographic and climate conditions of runoff formation differ significantly in the different parts of the basins of these rivers; however, the proposed models coped with this heterogeneity.

Table 2 gives the results of comparison of river runoff characteristics calculated by the tuned hydrological models and the observed characteristics of the annual and monthly river runoff (average annual runoff, standard deviation, and the coefficient of variation) in the Amur and Lena basins in the long periods mentioned above (Table 2; Fig. 2).

The errors in the simulated values were 5.2 for the average annual runoff of the Amur R. and 7.1% for its variations; the root-mean-square error in the annual

Table 1. The values of simulation quality criteria for the mean monthly and annual runoff in the Amur and Lena rivers over calibration/verification period

River-gage	F, ths. km^2	NSE	KGE	BIAS, %	BIASσ, %*	$BIAS_{CV}$, %*
Amur Basin						
Amur–Khabarovsk	1630	0.89/0.92	0.90/0.89	1.6/0.3	–9.1	–9.7
Amur–Bogorodskoe	1790	0.90/0.90	0.91/0.92	–5.7/0.7	1.5	2.9
Zeya–Belogorie	229	0.77/0.92	0.87/0.95	–4.9/–0.3	1.6	4.2
Zeya hydropower station	83.8	0.88/0.93	0.92/0.94	–0.8/0.7	2.8	2.5
Selemdzha–Ust-Ulma	67	0.81/0.84	0.79/0.80	–17/–18	–11	8.0
Bolshaya Ussurka–Vaguton	23	0.79/0.83	0.84/0.86	13/10	1.1	–9.5
Bikin–Zvenievoi	21.4	0.77/0.74	0.81/0.85	15/11	7.6	–4.8
Khor–Khor	24.5	0.82/0.79	0.68/0.59	–20/–26	–17	7.8
Bureya–Ust-Niman	26.5	0.93/0.93	0.85/0.92	–13/–6.5	–6.2	3.9
Bureya hydropower station	65.2	0.93/0.91	0.90/0.85	2.9/0.8	–1.0	–2.9
Area-weighted average		0.89/0.91	0.90/0.90	–2.5/0.1	–3.2	–2.3
Lena Basin						
Lena–Stolb	2460	0.98/0.97	0.96/0.96	–0.2/2.3	2.1	1.5
Lena–Kusur	2430	0.95/0.96	0.90/0.94	–6.9/–2.7	–0.9	4.3
Lena–Tabaga	897	0.91/0.90	0.84/0.85	–16/–15	–13	2.5
Lena–Krestovsky	440	0.79/0.80	0.72/0.74	–27/–25	–17	–12
Aldan–V. Perevoz	696	0.93/0.88	0.84/0.85	–2.7/10	2.6	–1.6
Vilyui–Khatyryk	452	0.85/0.69	0.74/0.64	17/25	–20	–34
Olekma–Kudu-Kuel	115	0.91/0.92	0.91/0.91	8.5/8.1	–3.3	–10
Area-weighted average		0.94/0.92	0.89/0.90	–4.9/–0.7	–3.2	–0.9

* $BIAS_{\sigma}$ and $BIAS_{CV}$ criteria were evaluated over the entire simulation period.

runoff over period 1970–1999 was 710 m^3/s, or 7% of the river runoff. The error in the simulated average annual Lena runoff was –1.6%, and that of its variations was 6%; the root-mean-square error of the annual runoff over period 1970–1999 was 1093 m^3/s or 6% of the river runoff. Figure 2 shows the calculated mean monthly runoff values for the examined rivers, averaged over the analyzed long periods, the so-called typical hydrographs. In the case of the Amur Basin, the model was found to overestimate the long-term average winter runoff and its variations; this was also the case in August in the period of rain floods. The root-mean-square error in the long-term average runoff of the Amur R. in different months was 1822 m^3/s or 17% and that in its standard deviation was 969 m^3/s or 32%; such error in the coefficient of variation was 0.10. In the case of the Lena R., the model commonly underestimates winter runoff variations and somewhat underestimates the long-term average runoff in June (the most water-abundant month) and its variations. The root-mean-square error in the long-term average Lena runoff in different months was 2190 m^3/s or 13%, those for the standard deviations were 459 m^3/s or 12%, and that of the coefficient of variation was 0.12.

Hydrometeorological Calculations Based on RHMs and GCMs

The numerical experiments with the developed runoff formation models with the data of GCMs did not take into account runoff regulation by reservoirs in the Amur and Lena basins, because the study was focused on evaluating the response of the natural hydrological system of the basins to climate changes. For example, as shown in [3], the difference in the long-term runoff hydrographs of the Amur R. at the

Table 2. Simulated characteristics of the annual runoff at the mouth gages by the developed hydrological models of the Amur and Lena basins over period 1970–1999

Characteristics	Amur		Lena	
	observed	simulated	observed	simulated
Average annual runoff, m^3/s	10829	11392	17067	16786
Standard deviation, m^3/s	2130	2280	2123	2250
Coefficient of variation	0.20	0.20	0.12	0.13

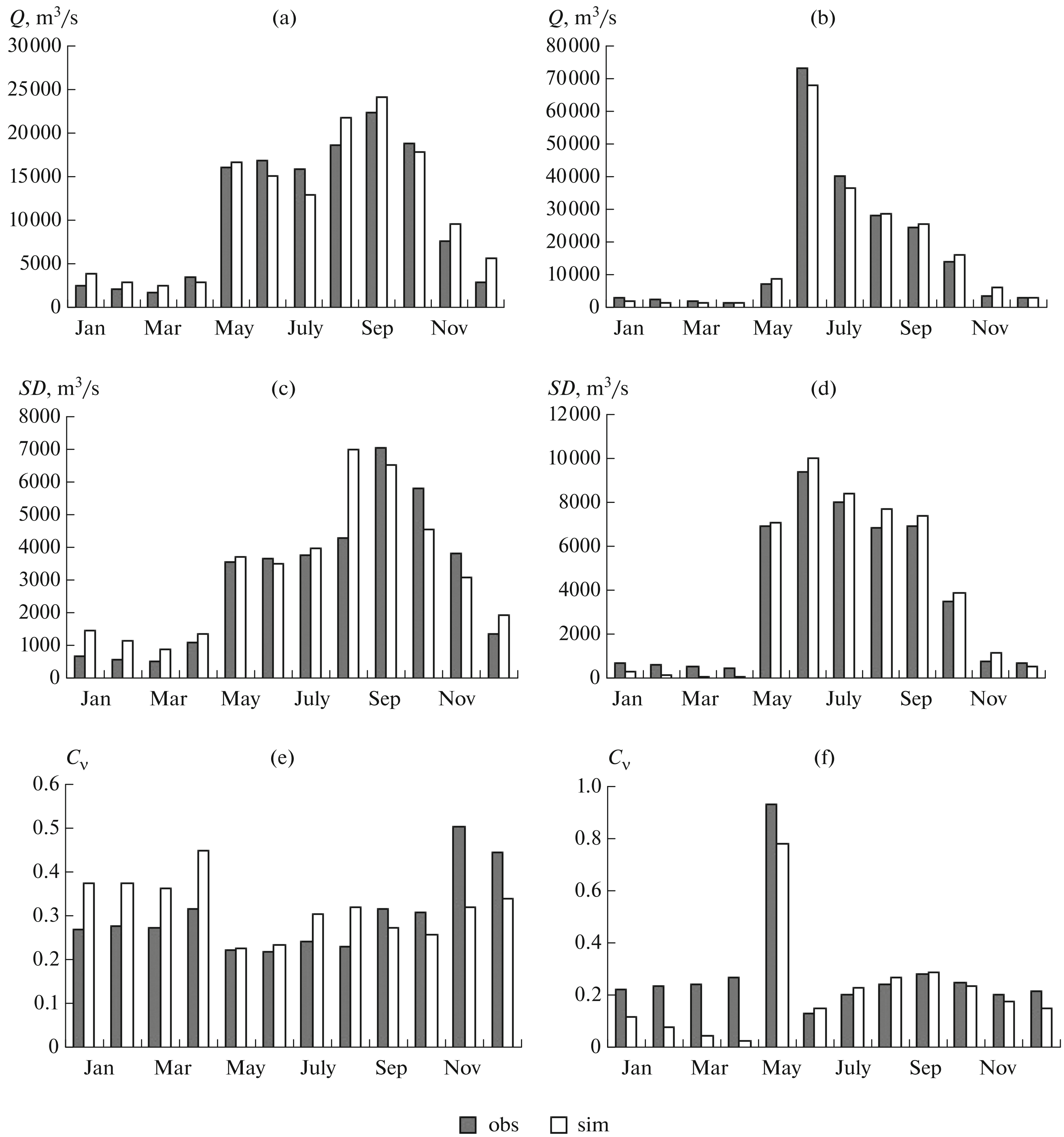

Fig. 2. Characteristics derived from the developed hydrological models of the Amur and Lena basins (1970–1999), including the long-term average, standard deviation, and the coefficient of variation of the mean monthly runoff at near-mouth gages: (a, c, e) for the Amur R. and (b, d, f) for the Lena R.

outlet gage, simulated with runoff regulation by all reservoirs taken and not taken into account is less than the relative error of the estimate of the Amur R. runoff by the data on water level.

The reliability of calculations of the future climate is believed to be determined by the ability of the models to reproduce its current state in accordance with the available observation data. With this taken into account, it was of importance to evaluate the accuracy of GCM-based reproduction of climate characteristics in the examined catchments, i.e., at the regional scale. To do this, the available data of simulation by climate models were compared with the data of meteorological observations. The calculated basin-averaged long-term norms of meteorological values (precipitation, surface temperature, and air humidity deficit) were compared over the historical period. In the examined river basins, the climate models reproduce the norms of meteorological characteristics with a high accuracy. The error in air temperature by GCMs data was 0.1–0.2°C; that of total precipitation was up to 3%; and that of air humidity deficit, up to 5%. In this case, some scatter was observed in the norms of meteorological values calculated by the data of different climate models over the same period. This is due to the model uncertainty caused by the difference between climate models in terms of the parameterization of individual processes, numerical schemes, etc., resulting in somewhat different results at the same forcing. To reduce the uncertainty of climate characteristics in different models, ensemble approach was used, i.e., the results of calculations by several models were averaged to obtain more reliable estimates.

In addition to the long-term averages of the annual meteorological characteristics, the accuracy of their seasonal variations was estimated. To do this, the long-term averages of the mean monthly values of air temperature, air humidity, and precipitation, averaged over the Amur and Lena basins were calculated. For two river basins, the seasonal variations of air temperature are reproduced by the model most accurately. The precipitation is overestimated by GCMs by 25 and 14% in winter and underestimated by 4 and 3% in period from June to September for the Amur and Lena basins, respectively, compared with weather stations data (Fig. 3). According to GCMs data, the deficit of air humidity is underestimated in winter by 12 and 16% for the Amur and Lena basins, respectively, and overestimated in the warmest periods (July, August) by 8 for the Amur R. and 9% for the Lena R.

At the next stage, the series of the average daily meteorological characteristics, calculated by four climate models over period 1970–1999 were specified as input data to runoff formation models, which were used to calculate water regime characteristics of the examined rivers under the present-day climate. The calculated characteristics of the annual and seasonal runoff were compared with those derived from observations at weather stations.

The errors in the reproduction of the seasonal variations of meteorological characteristics by GCM data compared with the data of observations have resulted in errors in calculating the seasonal characteristics of river runoff (Fig. 3). The long-term average hydrographs of mean monthly runoff, calculated by the data of climate models over the basic period, overestimate the runoff during spring flood passage by 22% relative to the Amur R. runoff evaluated using data of weather station observations and underestimate it by 6% for the period of summer–autumn floods. In the case of the Lena R., GCMs data yield an overestimate of the runoff in the most water-abundant month (June) by 10%. Overall, the calculations showed that the data of climate models can be used to reproduce the typical runoff regime in the outlet gages of the examined rivers.

Unlike the errors in seasonal runoff calculation, the estimates of the long-term average annual runoff with the use of data of climate models over the basic period proved much more accurate (Table 3). The relative error in the calculation of Amur R. runoff by the data of an ensemble of GCMs compared with the calculations based on weather observation data averaged 2.5% with errors for individual models up to 5%. The error in Lena R. runoff calculation, on the average for GCMs, is 3.7% with errors in individual models up to 6%.

In addition, we evaluated the reproduction of variability characteristics of the annual runoff based on data of climate models. The relative errors of the standard deviation and the coefficient of variation of the Amur R. runoff are differently directed for individual GCMs at the average values over the ensemble of 0.2 and –2.3%, respectively (Table 3). For the Lena R., the characteristics of runoff variations by GCMs data are underestimated and amount to –13% by the standard deviation of the annual runoff and –16% by the coefficient of variation.

After that, estimates were made for the time variations of the annual runoff of the Amur and Lena rivers, calculated by data of weather stations and data of an ensemble of climate models over the historical period (Fig. 4). The correlation between the runoff values calculated by data of weather stations and the average over GCMs ensemble were 0.02 for the Amur R. and 0.20 for the Lena R., i.e., the series do not correlate with one another. The variation range of the coefficient of correlation for calculations by different climate models was –0.35 to 0.18 for the Amur R. and –0.07 to 0.25 for the Lena R. This can be explained by that the climate models do not reproduce the specific features of weather in individual years, a feature that inevitably has its effect on river runoff calculation by hydrological models.

The possibility to reproduce the trend observed in the series of the annual runoff of the examined rivers was also assessed. No statistically significant trend was found to exist in the runoff in the period under consideration. The annual runoff of the Amur R., calculated by the observation data of weather stations over 1970–1999 shows a positive trend of 1.6 km^3/year; the trend in the series by the ensemble of climate models was 0.9 km^3/year, and that for the observed runoff with regulation by reservoirs taken into account was 2.6 km^3/year. The annual runoff series of the Lena R., calculated by weather station observations over period 1970–1999, by the ensemble of GCMs, and by the observed runoff with regulation by reservoirs taken

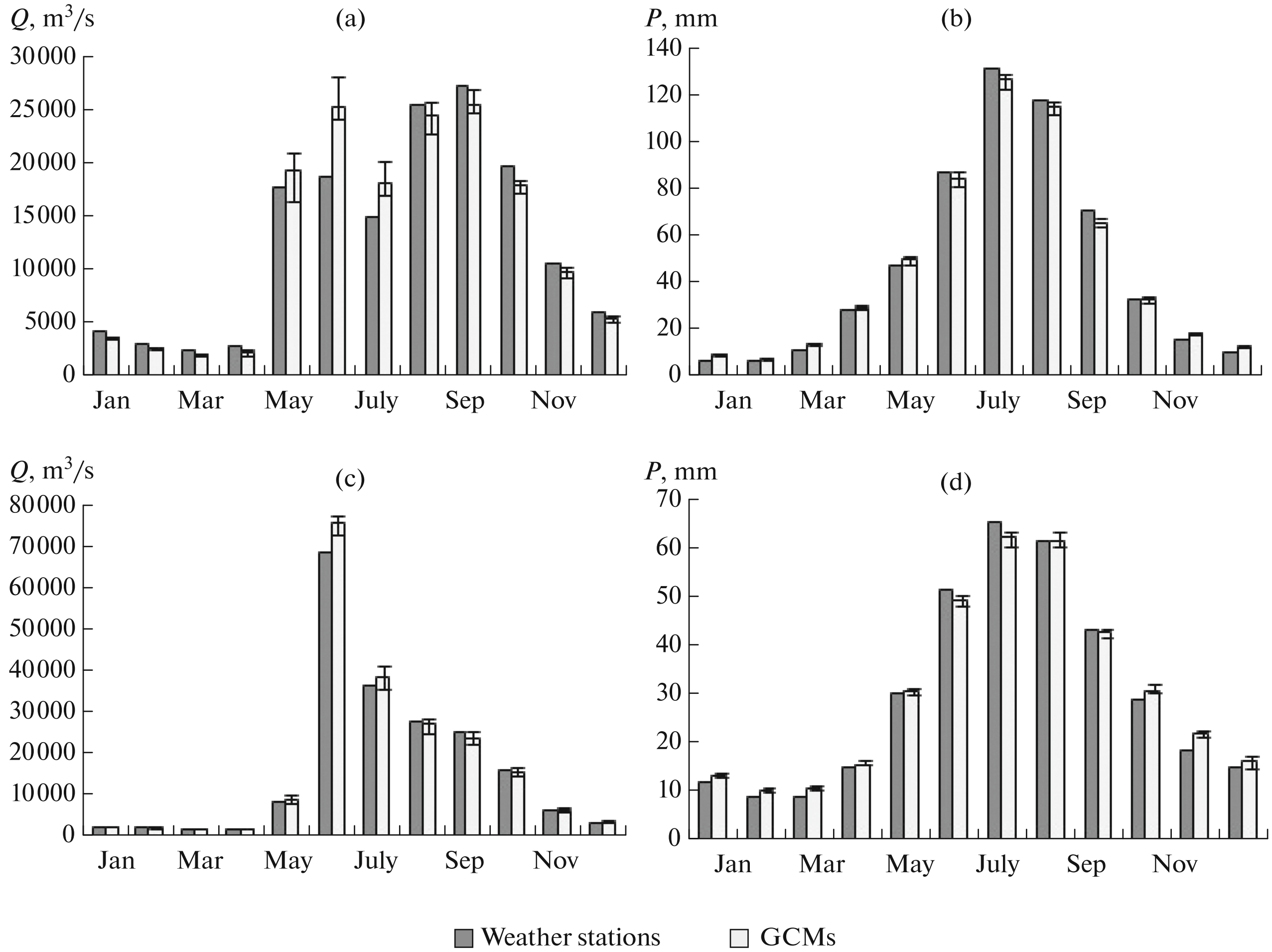

Fig. 3. Long-term average seasonal variations of river runoff and basin area-averaged precipitation, constructed by observational data and the average over the ensemble of climate models with the specification of the range of estimates by different GCMs over historical period 1970–1999 (the Amur R. (a, b), the Lena R. (c, d)).

into account shows positive trends of 2.2, 3.6, and 0.6 km^3/year, respectively.

The spatial accuracy of river runoff calculations by climate model data over a long period was evaluated with the use of the coefficient of spatial correlation. The fields of the average long-term runoff modulus, constructed by the calculation results of the runoff formation model for elementary catchments in the examined basins by data of weather stations and by data of GCMs were compared. The spatial coefficient of correlation for such field by data of GCMs ensemble was 0.94 for the Amur R. and 0.90 for the Lena R.

CONCLUSIONS

Hydrological models yielded good or satisfactory results (NSE > 0.5, KGE > 0.5, |BIAS| < 15%) in the calculation of the average monthly and annual runoff by criteria NSE and KGE for each of the 17 gages (including 11 on tributaries) by criteria BIAS, BIAS$_\sigma$, BIAS$_{CV}$ for 12, 14, and 16 gages, respectively. Calculation results were classified as unsatisfactory by criteria of systematic error of the annual runoff (the Khor, Selemdzha, Vilyui rivers and the gages Krestovsky and Tabaga on the Lena R.) and its variations (the Khor, Vilyui rivers and Krestovsky gage) in the catchment area small compared with that of other gages. This effect may be due to the neglect of some local features of river runoff formation, typical of those rivers, including the features of under-ice period. The values of statistical criteria, averaged with weights proportional to the catchment areas of the examined rivers, show the good estimation accuracy of river hydrographs in the Amur and Lena basins over the observation period by data of weather stations. In addition, the quality criteria show low sensitivity in the passage from calibration to verification periods, thus suggesting the robustness of the models.

The analysis of the agreement between the actual characteristics of the annual and average monthly river runoff (norms of annual runoff, standard deviation, and the coefficient of variation) at the near-mouth

Table 3. Long-term averages of the annual runoff and its variations for the Amur and Lena rivers, calculated by hydrological models and climate model data over the historical period, with relative errors in the calculation of water regime characteristic

Type of meteodata	Q_{AV}, m^3/s	SD, m^3/s	Cv	BIAS Q_{AV}, %	$BIAS_{SD}$, %	$BIAS_{CV}$, %
			Amur River			
Weather stations	12687	2476	0.20		–	
GFDL-ESM2M	12911	2008	0.16	1.8	−19	−20
HadGEM2-ES	13052	2932	0.22	2.9	18	15
IPSL-CM5A-LR	13363	2374	0.18	5.3	−4.1	−9
MIROC-ESM-CHEM	12696	2609	0.21	0.1	5.4	5.3
GCMs ensemble	13005	2481	0.19	2.5	0.2	−2.3
			Lena River			
Weather stations	16758	2216	0.13		–	
GFDL-ESM2M	17631	2150	0.12	5.2	−3	−7.8
HadGEM2-ES	16612	1683	0.10	−0.9	−24	−23
IPSL-CM5A-LR	17779	1797	0.10	6.1	−19	−24
MIROC-ESM-CHEM	17468	2120	0.12	4.2	−4.3	−8.2
GCMs ensemble	17373	1938	0.11	3.7	−13	−16

gages over the historical period and their estimates by the hydrological models developed for the Amur and Lena basins showed the results to be satisfactory. The errors in the calculation of the norm of annual runoff of the Amur R. and its variations were 5.2 and 7.1%, respectively; the respective characteristics for the Lena R. were −1.6 and 6%. For the examined river basins, the climate models reproduce the norms of values of meteorological characteristics, averaged over the areas of river catchments, with a high accuracy. The error in determining air temperature by GCMs data was 0.1–0.2°C, and those of the total precipitation and air humidity deficit were up to 3 and 5%, respectively. To reduce the intermodel uncertainty of climate characteristics, ensemble approach was used, i.e., the results of calculations by several models were averaged to obtain more stable estimates.

In the examined river basins, the reproduction of the seasonal variations of air temperature by climate models is most accurate. The precipitation in the Amur and Lena basins was overestimated by GCMs in winter by 25 and 14% and underestimated in period from June to September by 4 and 3%, respectively, compared with the observation data from weather stations. GCMs data underestimate air humidity deficit in the Amur and Lena basins by 12 and 16% in winter and overestimates it by 8 and 9% in the warmest months (July and August), respectively.

Calibrated hydrological models show a satisfactory accuracy in the estimates of the norm of annual runoff of the examined rivers over the historical period with boundary conditions derived from the data of ensemble calculations of GCMs. The relative error in the calculation of ensemble-averaged norm of the Amur R. runoff compared to that calculated by weather observation data was 2.5, and that for the Lena R. was 3.7%. The relative errors of the standard deviation and the coefficient of variation of Amur R. runoff have different signs for individual GCMs at the ensemble averages of 0.2 and −2.3%, respectively. In the case of the Lena R., the characteristics of runoff variations by GCMs data are underestimated and amount to −13 for the standard deviations of the annual runoff and −16% by its coefficient of variation. The average long-term

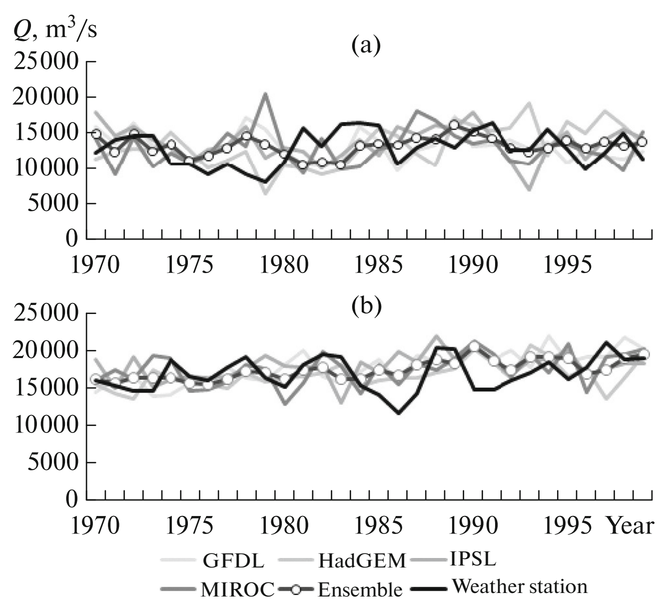

Fig. 4. Time variations of the annual runoff of (a) the Amur R. and (b) the Lena R., calculated by weather station data and data of an ensemble of climate models over the historical period.

hydrographs of Amur monthly runoff, calculated by the data of climate models over the basic period overestimate the runoff during the passage of spring flood wave by 22%, compared with the runoff calculated by the data of weather station observations, and underestimate this runoff during summer–autumn freshets by 6%. In the case of the Lena R., the runoff estimates by GCMs data in June, the most water-abundant month, is overestimated by 10%. Overall, the calculations showed that the data of climate models were successfully used to reproduce the average long-term seasonal runoff regime in the outlet gages of the examined rivers.

The calculation quality of the trend in the annual runoff of the rivers over the historical period with the use of data of an ensemble of climate models can be characterized as satisfactory. The annual runoff of the Amur R., calculated by the observations at weather stations over 1970–1999 shows a positive trend of 1.6 km^3/year; that by the ensemble of climate models is 0.9 km^3/year, and that for the observed runoff with regulation by reservoirs taken into account is 2.6 km^3/year. For the annual runoff of the Lena R., the positive trends by the observation data of weather stations, GCMs ensemble, and the observed runoff with regulation by the Vilyui Res. taken into account are 2.2, 3.6, and 0.6 km^3/year, respectively. The spatial coefficient of correlation between the field of the norm of specific discharge, calculated by an ensemble of GCMs, and the same fields constructed by observation data, was greater than 0.9 for both basins. Therefore, GCMs reproduce the regional features of the atmospheric circulation in the examined river basins and the specific features of runoff formation calculated by hydrological models.

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