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The Impact of Climate Change on Surface, Subsurface, and Groundwater Flow: A Case Study of the Oka River (European Russia)

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Abstract—The article considers an approach to evaluating the change in surface, subsurface and groundwater flow on a large river catchment exemplified by the Oka River basin. The study is based on the synthesis of a physical-mathematical model of runoff formation and atmosphere–ocean general circulation models. The paper presents the results of calibration and verification of a hydrological model over a period of history, as well as the assessment of reproduction accuracy of meteorological and hydrological characteristics according to the data of global climate models and observation data. Based on an ensemble of atmosphere–ocean general circulation models, the changes in meteorological (air temperature, precipitation, air humidity deficit) and hydrological (surface runoff, soil moisture content, groundwater flow) characteristics by the middle and the end of the 21st century have been calculated, under the scenarios RCP 2.6 and RCP 6.0 with regard to the historical period.

Keywords: runoff formation model, climate change, the Oka River, surface, subsurface and groundwater flow

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INTRODUCTION

Studying the patterns of water resources formation and changes for the purpose of long-term forecasting of water availability in territories, taking into account the increasing anthropogenic impact on water objects under climate change, is an urgent task. Hydrological models help to assess changes in river water regime using the calculations of current atmosphere–ocean general circulation models (GCMs).

The application of spatially distributed physical mathematical models of runoff formation, which describe all the main processes of the hydrological cycle, provides information not only about changes in surface water resources, but also about runoff components, for instance, changes in soil moisture storage or groundwater, which is extremely important for planning agricultural activities in the central and southern regions of European Russia.

Evaluation of model accuracy of subsurface and groundwater flow calculations is complicated by the presence of quite rare data sets, in contrast to surface runoff. River flow is measured on a hydrometric network, then the data are published in official sources. The necessary detail measurements of subsurface and groundwater flow are realized either on a network of water balance stations or during local field studies, undertaken by certain scientific teams. Both data sets correspond to smaller catchments. There are, however, chemical statistical methods of assessing the input of separate runoff components, which are based on using different combinations of chemical tracers. End-Member Mixing Analysis (EMMA) is the most common methodology of this kind (an overview of studies is given, for example, in [2, 6]). Nevertheless, its application is complicated by the prevalence of non-conservative chemical elements and expensive isotopic analysis. Moreover, in [2] it is shown that the uncertainty of the choice of tracer composition for solving a particular task is very high, and the major ions are not necessarily "useful" tracers, which leads to false conclusions about watershed runoff.

Furthermore, there is an approach to determining the surface, subsurface and groundwater components of runoff, based on lumped and spatially distributed hydrological models. The former have a significant limitation—when calibrating the value of many parameters, they can exceed the physical scope, whereas the latter are quite demanding with regard to the background information. A number of papers based on using hydrological modelling of runoff components present the results of calculation accuracy assessment only according to discharge data, while there are no verification data on subsurface and groundwater flow. However, the experimental results of comparing different models in the article [8] demonstrated consistency in the results for runoff components for slopes with a simple topography. In case of a more complex topography, the results can be reliable only on the qualitative level. Experiments have been carried out in order to compare the calculation accuracy of subsurface and groundwater flow both with the help of land surface and hydrological models separately and by integrating land surface and groundwater models. The difference in calculating subsurface and groundwater flow between land surface and hydrological models significantly increases at a depth of more than 30 cm [10]. The advantage of integrating land surface and groundwater models consists in a more accurate description of underground water, as shown by the example of the Valdai water balance station [7]. Nevertheless, studies of surface, subsurface, and groundwater flow—both with chemical statistical approaches and different hydrological and hybrid models—confine themselves to smaller catchments with an average area of up to 1000 km^2. So the question immediately presents itself: how to deal with evaluation for major rivers? This article shows the results of application of an approach to calculating surface, subsurface and groundwater flow in the Oka R. basin.

The study was focused on the basin of the Oka R.—the largest right tributary of the Volga R. and one of the most populated regions of European Russia. The total catchment area of the Oka R. basin is 245 thous. km^2. The Oka Basin lies between 52° and 57° N, 33° and 45° E. The Oka Basin belongs to the central part of the East European Plain with a moderate continental climate. The mean absolute height of the catchment is 170 m a.s.l., the long-term average air temperature is 5.4°C, the amount of precipitation is 600 mm. The mean annual discharge at the mouth is 1340 m^3/s. The river regime is characterized by high spring flood caused by snowmelt on the catchment area. In some years, there may be summer–autumn rain floods, as well as thaw-induced winter floods. However, on the long-term average scale, except April and May, the runoff has a fairly uniform distribution throughout seasons. The runoff of some tributaries of the Oka R. (the Moskva and Klyazma rivers) is regulated by several smaller reservoirs created primarily in order to supply the population with water. Given below are the results of assessing the changes in the regime of the Oka R. under the influence of climate as a natural system, excluding the possibility of regulating the runoff.

A lot of scientific works are devoted to the evaluation of changes in the Oka R. runoff under the influence of climatic characteristics. In them, the research is carried out based on observation data, i.e. over a historical period. For instance, the article [5] presents the conclusion about a significant increase in the Oka R. winter runoff with a simultaneous decrease in the runoff over the period of spring floods. At the same time, physical mathematical models of runoff formation had been earlier elaborated for the Oka Basin [1] and in particular for the Cheboksary reservoir [3], using the Russian databases of the ECOMAG, which could be used as an instrument for assessing the hydrological consequences of climate change. The present paper suggests a methodology of calculating physically possible changes in surface, subsurface, and groundwater flow in the Oka Basin, based on the synthesis of the runoff formation model elaborated according to the global databases, and current atmosphere–ocean general circulation models, during the 21st century.

DATA AND METHODS

The runoff formation model was developed based on the ECOMAG software [9] with a daily time step and a spatial resolution of the computation grid size (elementary catchments). Such characteristics are sufficient to describe the spatial distribution 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, subsurface and groundwater flow in the catchment.

The information sources about the parameters of the underlying surface necessary for the schematization of the watershed were the global databases of the relief, soils, and land use. The average area of the estimated model elements amounted to 1600 km^2. The base of meteorological source data includes time series of mean daily values of the surface air temperature, precipitation, and air humidity deficit, measured at 75 weather stations in the Oka R. basin. The agreement between the simulated and observed daily and monthly runoff was evaluated using the Nash–Sutcliffe criterion (NSE), and the relative error of mean annual runoff calculation (BIAS). Runoff hydrograph simulation is good at $0.7 \le NSE \le 1$, $|BIAS| \le 10\%$.

For the numerical experiments with the developed hydrological model, meteorological characteristics had been calculated by the ensemble of GCMs CMIP5 based on the results of Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) 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 primarily calculated mean daily meteorological values in four climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5) over the historical period into the data of reanalysis ERA–Interim in the regular grid 0.5° [4].

RESULTS AND DISCUSSION

Calibration and Validation of the Hydrological Model

Model parameters for the Oka R. basin were calibrated for the period 2000–2014 at the outlet Gorbatov gauging station with the catchment area of 244 thous. km^2 (Fig. 1; Table 1). The model was veri-

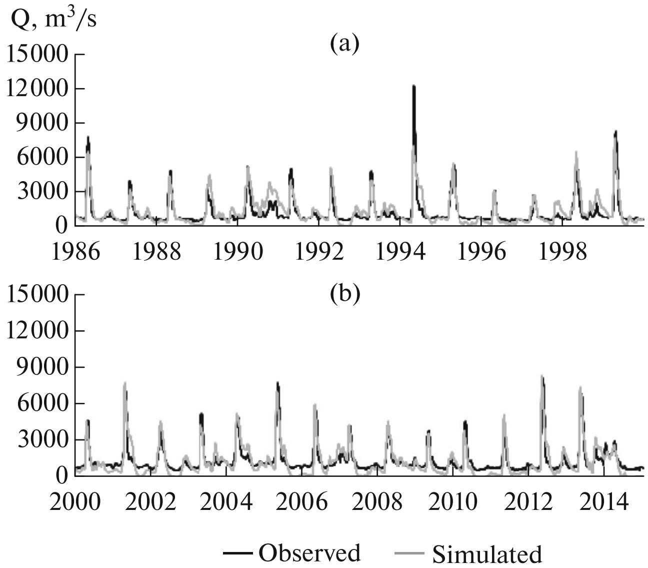

Fig. 1. Observed and simulated daily runoff of the Oka R. over (a) the verification and (b) calibration periods of the hydrological model.

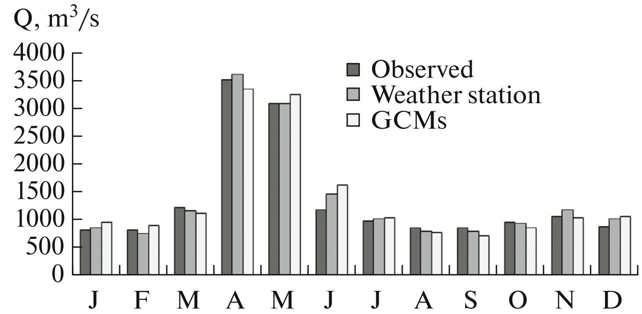

Fig. 2. Long-term average monthly runoff of the Oka R.: observed, simulated based on weather stations and GCMs ensemble data over the historical period 1986–2005.

fied with independent measurement data over the period 1986–1999. Table 1 also demonstrates the results of calculation accuracy verification of the Oka R. runoff for the overall period 1986–2014 and for the period 1986–2005, which had been chosen as a historical reference for the subsequent assessment of river regime reproduction according to the GCMs data. The values of the criteria indicate that model calculations are sustainable during the transition from one period to another (NSE > 0.7, |BIAS| < 10%).

Since the designed model was further used for assessing the hydrological consequences of climate change, an additional testing was conducted on contrasting climatic periods according to the procedure suggested by V. Klemes. For this purpose, over the period 1986–2014, the long-term mean air temperature in the Oka Basin was estimated at 5.4°C with a range from –2.8 to 1.4°C for individual years, and the annual precipitation was estimated at 607 mm with a range from –29 to 24% for individual years. Then, depending on the increase/decrease in the analyzed values, the 29 years were divided into 4 categories: 10 warm–wet years (1989, 1990, 1995, 2000, 2001, 2004, 2005, 2008, 2012, 2013), 5 cold–wet years (1993, 1997, 1998, 2003, 2006), 8 warm–dry years (1991, 1999, 2002, 2007, 2009, 2010, 2011, 2014), and 6 cold-dry years (1986, 1987, 1988, 1992, 1994, 1996). The results for the four year groups, calculated by the criteria NSE and BIAS, are demonstrated in Table 2. The best results correspond to the cold–dry period, and the worst, to the cold–wet period, which is mainly due to the accuracy of estimating rain-related summer–autumn floods. On the whole, the results of model testing allow one to apply the model for conducting numerical experiments using the GCMs data.

Figure 2 shows mean monthly hydrographs of the Oka R. runoff, calculated according to the measurements of the runoff, data from weather stations and GCMs, which were averaged over the long-term reference period of 1986–2005. It is clear that the discrepancy between the estimated and the observed values is largest in June, i.e. according to the model data, the decline in floods is slightly behind the schedule. In other months, irregularities do not exceed 10–15%.

Hydrometeorological Calculations Based on Weather Stations and GCMs Data

The reliability of future climate calculations is believed to be determined by the ability of the GCMs to reproduce current climate conditions in accordance with the available observation data at the regional scale. In turn, the hydrological model helped to estimate the reproduction of seasonal and annual long-term average surface, subsurface, and groundwater flow, calculated with boundary conditions according to weather stations and GCMs data. The calculated basin-averaged long-term norms of meteorological (air temperature, precipitation, and air humidity deficit) and hydrological (topsoil moisture content and groundwater flow) values and surface river runoff cal-

Table 1. The values of simulation quality criteria for the daily, monthly and annual Oka R. runoff over the calibration/verification period

Period	NSE		BIAS, %
	daily	monthly	
1986–1999	0.72	0.74	5.6
2000–2014	0.74	0.76	–5.4
1986–2014	0.73	0.75	–0.2
1986–2005	0.73	0.75	3.0

Table 2. The values of simulation quality criteria for the daily, monthly, and annual Oka R. runoff over the contrasting climatic periods in 1986–2014

Period	NSE		BIAS, %
	daily	monthly	
Warm–wet	0.71	0.73	7.4
Cold–wet	0.66	0.68	12
Warm–dry	0.72	0.74	–13
Cold–dry	0.79	0.81	–9.1

culated at an outlet gauging station were compared over the historical period of 1986–2005.

The division into seasons was realized in accordance with the meteorological and hydrological regime in the Oka Basin in the following way: winter runoff (November–March), spring flood (April–May), summer–autumn flow (June–October). First, the calculations were performed for every GCM individually, then they were averaged over the ensemble.

The climate models reproduce the norms of annual meteorological and hydrological characteristics with a high accuracy: the error was 0.4°C in the air temperature, –1.7% in the precipitation, 3.2% in the air humidity deficit, –0.2% in the surface runoff, 3.6% in groundwater flow, and –1.4% in the topsoil moisture content. Considering the conformity of the estimated seasonal values, one can see that the error is up to 0.7°C in the summer–autumn air temperature, 7–10% in precipitation, 5–18% in air humidity deficit, up to 1% in surface runoff, 1–11% in groundwater flow, and up to 2% topsoil moisture content, depending on the season (Fig. 3). Therefore, the GCMs reproduce the regional features of the seasonal atmospheric circulation in the Oka R. basin and the specific features of runoff formation calculated by the hydrological model.

Future Anomalies of Seasonal and Annual Hydrometeorological Characteristics

The ensemble of the GCMs was used to estimate possible changes in the climatic and hydrological characteristics in the Oka R. basin during the 21st century. The GCMs meteorological data were used, based on the two RCP scenarios: RCP 2.6 and RCP 6.0. The elaborated model of runoff formation helped to make calculations for the 21st century with the same parameters as were set when carrying out calculations for a historical period.

Changes in the climatic and hydrological characteristics in the Oka Basin during the 21st century were estimated by calculating anomalies of these values, i.e. a relative change in comparison with the values of the reference period 1986–2005 for every GCM. After that, the values were averaged in accordance with the ensemble and 20-year periods, corresponding to the middle (2040–2059) and the end (2080–2099) of the 21st century. The results of the change in the norms of seasonal and annual basin-averaged meteorological characteristics are presented in Fig. 4.

The results of calculations with the ensemble GCMs demonstrated that a possible rise in the temperature will amount to 2–2.5°C by the middle of the century under the scenarios RCP 2.6 and RCP 6.0, and will exceed 4°C at the end of the 21st century, while annual precipitation will increase by almost 10% according to the RCP 6.0 scenario. An increase in the air humidity deficit by the middle of the century will be 25% according to both scenarios; and by the end of the century, 34 and 43%, according to the RCP 2.6 and RCP 6.0, respectively. The fastest rate of warming during the 21st century is observed for winter and spring. Precipitation over the winter period will increase by 4–5% according to the scenario RCP 2.6, and by 6–13% according to the RCP 6.0, which also suggests that by the end of the 21st century, humidification will grow by 5% in spring and 8% in summer–autumn. The highest growth rates of air humidity deficit equal to 37–79% are obtained for winter, the lowest—by 22–36%—for the summer–autumn period.

Figure 5 gives the results of calculating changes in the norm of topsoil moisture content and groundwater flow, averaged across the basin area, and the Oka runoff at the outlet section, based on the hydrological model with the GCMs data for the 21st century. The calculation results on the ensemble GCMs demonstrated that a possible reduction in the annual Oka R. runoff would be 25–30% by the middle of the century according to both scenarios. By the end of the 21st century, it will amount to 18% according to the RCP 2.6 and to 22% according to the RCP 6.0.

In the article [5], it is noted that over the last 35 years, the annual Oka runoff has increased by 18% in regard to the similar (in length) earlier period, i.e. the forecasted runoff reduction will lead to the return of the Oka runoff approximately to the characteristics corresponding to the middle of the 20th century, but given its significant intra-annual transformation. In this case, the change in soil moisture content will not exceed 3% according to both scenarios, by the middle and the end of the century. A decrease in the norm of groundwater flow will amount to 12–17% by mid-century and about 9% by the end of the century according to both scenarios. The most likely reason for the reduction of the Oka R. runoff is an increase in evaporation.

Considering the changes in seasonal values of surface, subsurface and groundwater runoff, one should note the fastest rates of groundwater flow growth in winter by 25–67% and its decrease in other seasons,

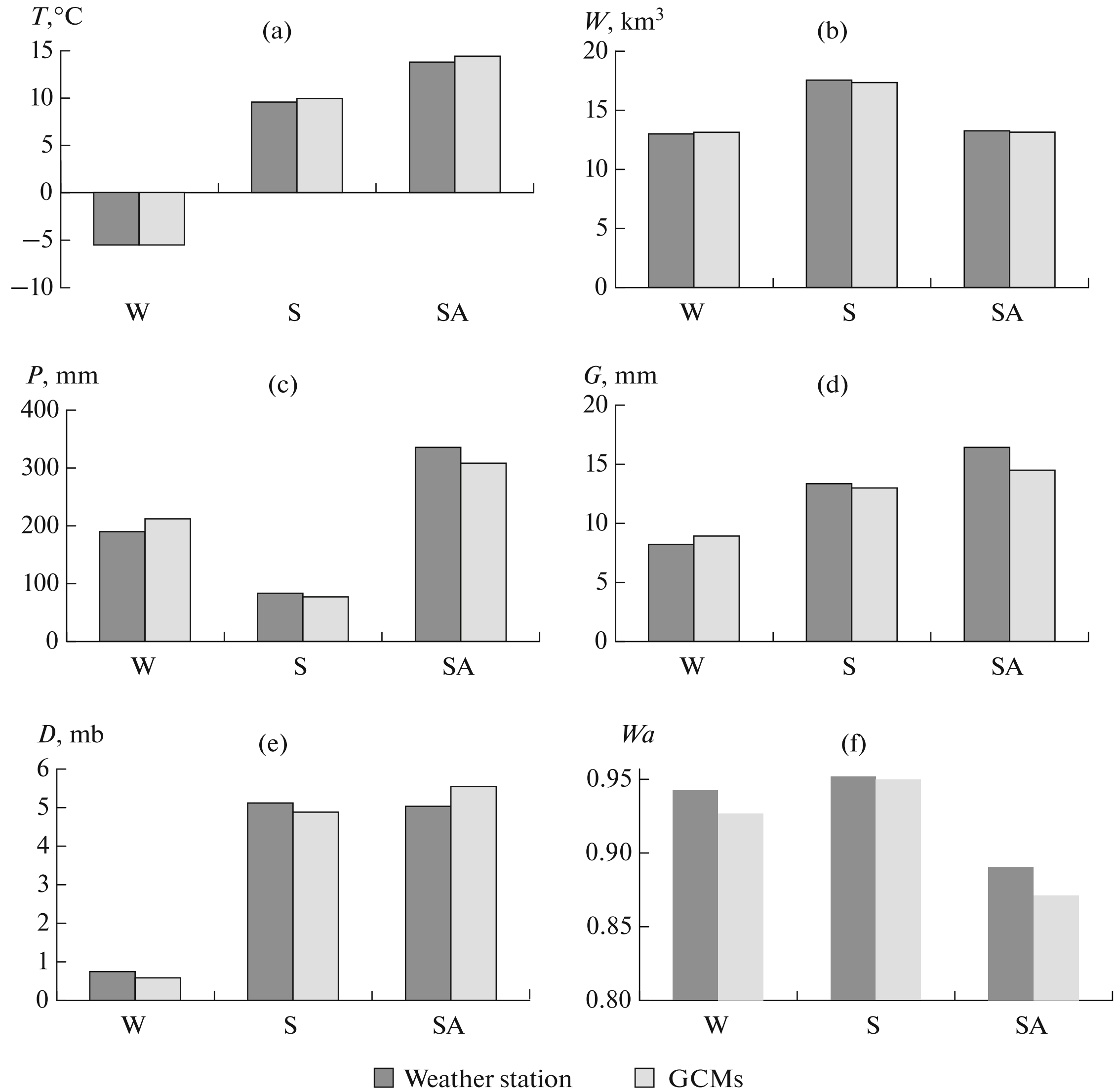

Fig. 3. Long-term average seasonal hydrometeorological characteristics of the Oka R. basin, calculated by weather stations and GCMs ensemble data over the historical period 1986–2005: (a) air temperature, (b) runoff, (c) precipitation, (d) groundwater flow, (e) air humidity deficit, (f) the ratio of topsoil moisture content (W is for winter, S is for spring, and SA is for summer–autumn).

especially, in spring—by 38–59% with regard to the historical period. Changes in topsoil moisture content are characterized by a slight negative trend in all seasons with some prevalence in the summer–autumn period. The Oka R. winter runoff is expected to rise by 5% and 3% by the middle of the 21st century, by 17 and 37% by the end of the century according to the scenarios RCP 2.6 and RCP 6.0, respectively. The spring runoff will decrease by 30–50%, whereas the summer–autumn runoff will decrease by 40–50%, depending on the RCP-scenario and the period of the 21st century. In general, seasonal variation of the runoff is connected with earlier and more spread flooding, an increase in winter runoff due to winter thawing, the early transition of the air temperature to positive values, and a decrease in groundwater inflow during the summer–autumn period.

The changes in the annual and spring surface and subsurface runoff, summer–autumn subsurface flow and spring groundwater flow by the middle of the 21st century are statistically significant by the t-test (at the 5% level), if the scenario RCP 2.6 is realized. By the end of the 21st century, it is true for all the three runoff components during spring (Table 3). According to the scenario RCP 6.0, the significance of changes in the Oka Basin water regime will increase substantially; only the changes in the winter surface runoff, as well as in winter and summer–autumn groundwater flow by mid-century, will be statistically insignificant.

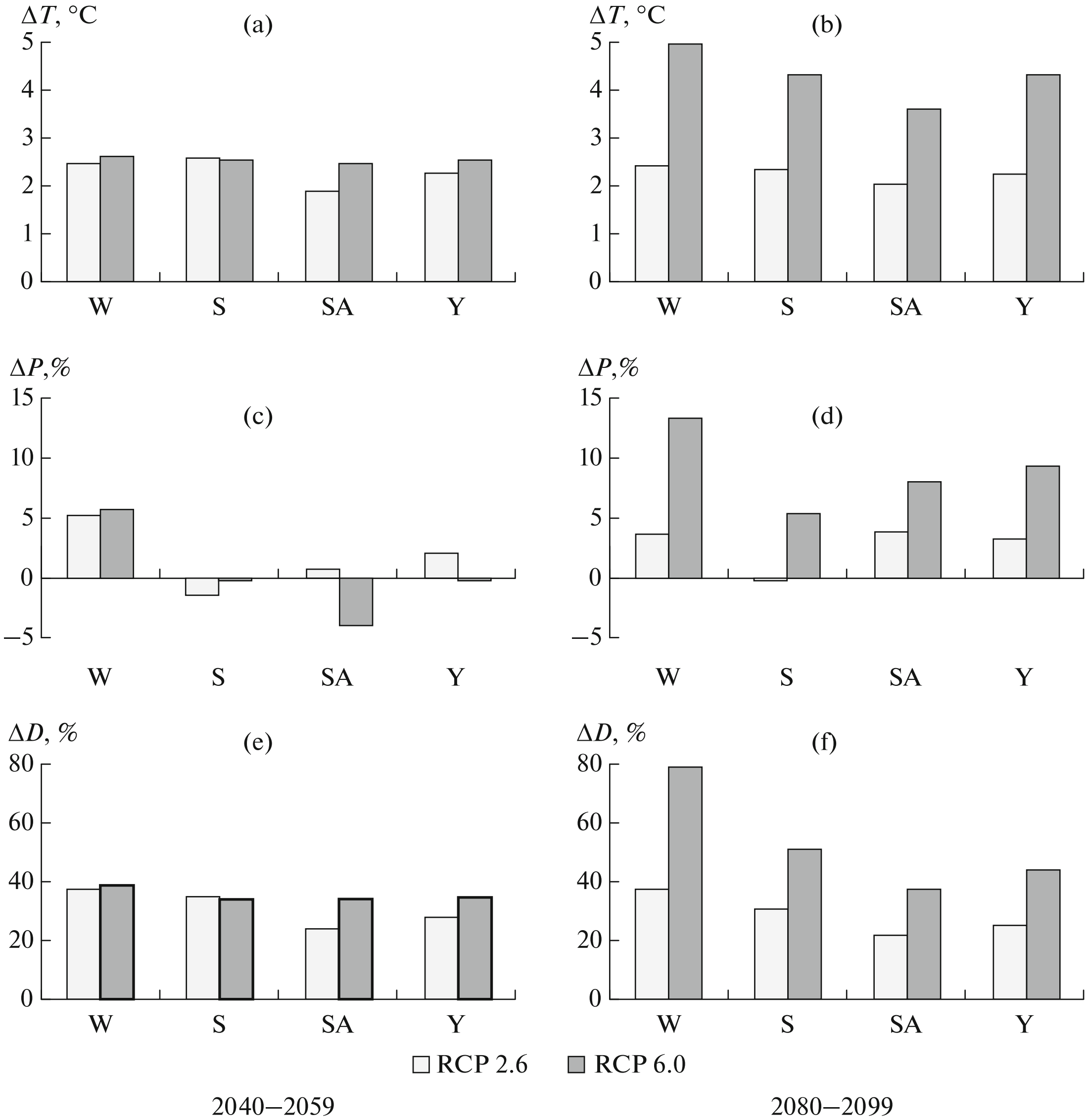

Fig. 4. Changes in the seasonal and annual norms of meteorological characteristics averaged across the area of the Oka R. basin, calculated on the ensemble GCMs data for the middle (2040–2059) and the end (2080–2099) of the 21st century under the scenarios RCP 2.6 and RCP 6.0 with regard to the corresponding values over the historical period 1986–2005: (a), (b) air temperature, (c), (d) precipitation, (e), (f) air humidity deficit (W is for winter, S is for spring, SA is for summer–autumn, and Y is for year).

As a result, during the 21st century, the Oka R. basin is likely to have a decrease in runoff by 20–30%, which will cause water supply deficit in the densely populated region of European Russia with developed industrial and agricultural infrastructure and will create negative preconditions for the development of economic activities and the population.

CONCLUSIONS

The Oka R. runoff formation model is based on global databases on the underlying surface with the involvement of observation data on the network of weather stations. The model is calibrated and verified on a long-term period of daily runoff observation data, successfully tested on contrasting climatic periods. Over the reference historical period, the accuracy of reproduction of annual and seasonal meteorological values was assessed on the GCMs data, with comparison with the data from weather stations in the Oka Basin; and the calculation of hydrological characteristics was evaluated based on two sets of meteorological information. According to the ensemble of GCMs, the error was 0.4°C in the average annual air temperature, −1.7% in precipitation, 3.2% in air humidity deficit, −0.2% in surface runoff, −3.6% in groundwater flow, and −1.4% in topsoil moisture content. The irregularity in seasonal values amounted to up to 0.7°C for the

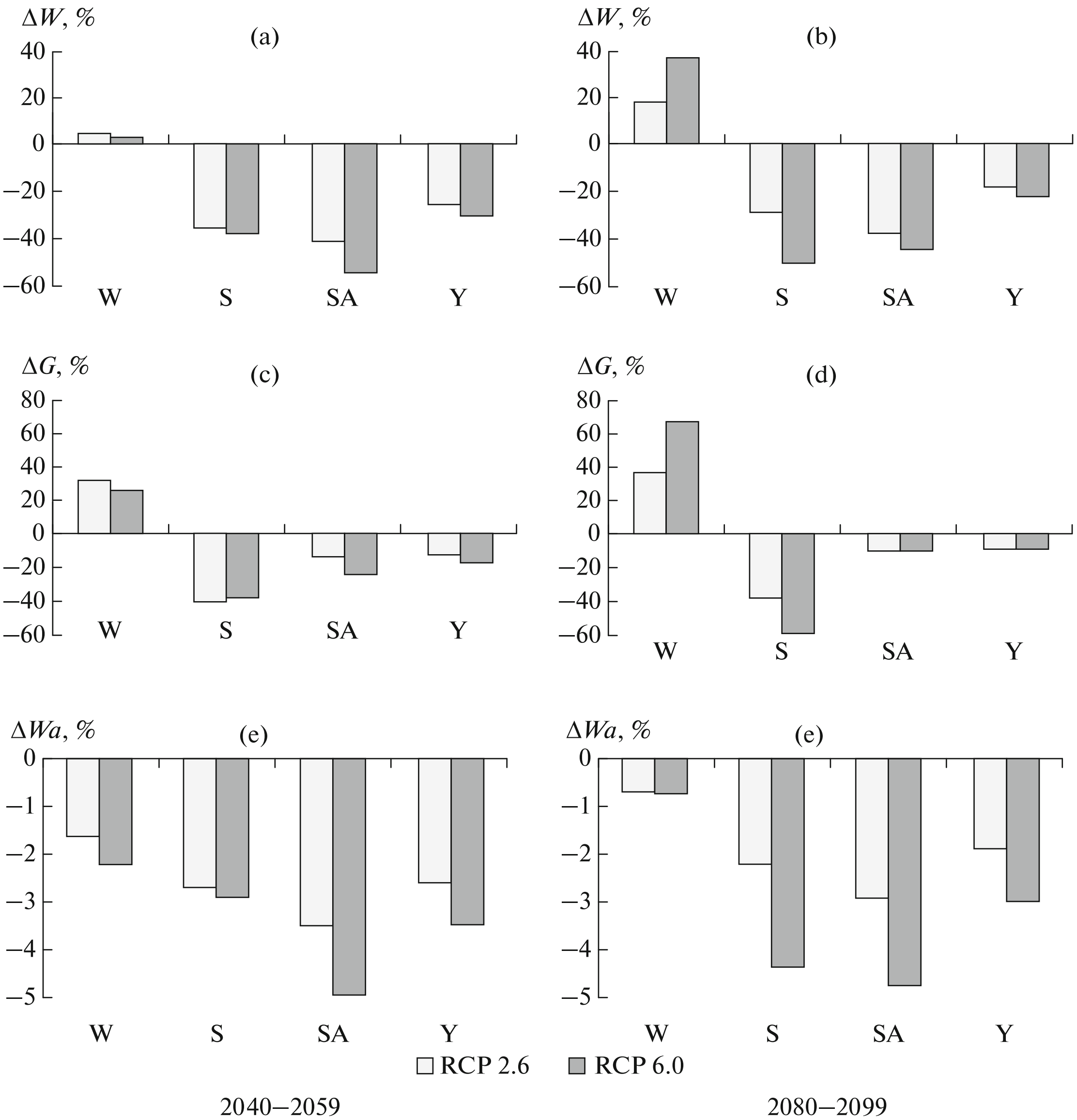

Fig. 5. Changes in seasonal and annual norms of topsoil moisture content and groundwater flow averaged across the area of the basin, and the Oka R. surface runoff, calculated on the ensemble GCMs data for the middle (2040–2059) and the end (2080–2099) of the 21st century under the scenarios RCP 2.6 and RCP 6.0 with regard to the corresponding values over the historical period 1986–2005: (a), (b) surface runoff, (c), (d) groundwater flow, (e), (f) ratio of topsoil moisture content (W is for winter, S is for spring, SA is for summer–autumn, and Y is for year).

summer-autumn air temperature, 7–10% in precipitation, 5–18% in air humidity deficit, up to 1% in surface runoff, 1–11% in groundwater flow, and up to 2% in topsoil moisture content, depending on the season.

The results of GCMs-based calculations demonstrated that a possible rise in temperature will be 2–2.5°C by the middle of the century according to the scenarios RCP 2.6 and RCP 6.0, will exceed 4°C at the end of the 21st century, while annual precipitation will increase by almost 10% under the scenario RCP 6.0. The increase in air humidity deficit will be 25% by mid-century according to both scenarios, 34 and 43% by the end of the century under the RCP 2.6 and RCP 6.0, respectively. A possible decrease in the annual runoff of the Oka R. will amount to 25–30% by the middle of the century under both scenarios, 18% under the RCP, and 2.6 and 22% under the RCP 6.0 by the end of the 21st century, respectively. The change in soil moisture content will not exceed 3% under both scenarios by the middle and by the end of the century. A decrease in the norm of groundwater flow will be 12–17% by the middle of the century and about 9% by its end under both scenarios. The most likely reason for the decrease in the Oka R. runoff is an increase in evaporation.

Table 3. Statistical significance (t-test) of change in the seasonal and annual norms of surface, subsurface, and groundwater flow in the Oka R. basin for the middle (2040–2059) and the end (2080–2099) of the 21st century under the RCP 2.6 and RCP 6.0 scenarios (W is winter, S is for spring, SA is for summer-autumn, and Y is for year)

Scenario	Period	Surface flow				Subsurface flow				Groundwater flow			
		Y	W	S	SA	Y	W	S	SA	Y	W	S	SA
RCP 2.6	Middle XXI	+	–	+	–	+	–	+	+	–	–	+	–
	End XXI	–	–	+	–	–	–	+	–	–	–	+	–
RCP 6.0	Middle XXI	+	–	+	+	+	+	+	+	+	–	+	–
	End XXI	+	+	+	+	+	+	+	+	+	+	+	+

For seasonal values, the fastest rates of groundwater flow growth were observed in winter—by 25–67%, while the runoff decrease is larger in other seasons, but especially, in spring—by 38–59% with regard to the historical period. Changes in topsoil moisture content are characterized by a slight negative trend in all seasons with some prevalence in the summer–autumn period. The Oka R. winter runoff will rise by 5 and 3% by the middle of the 21st century and by 17 and 37% by the end of the century under the scenarios RCP 2.6 and RCP 6.0, respectively. The spring runoff will decrease by 30–50%, whereas the summer–autumn runoff will decrease by 40–50%, depending on the RCP-scenario and the period of the 21st century.

The changes in the annual and spring surface and subsurface runoff, summer–autumn subsurface flow, and spring groundwater flow by the middle of the 21st century are statistically significant, if the scenario RCP 2.6 is realized. By the end of the 21st century, it is true for all the three runoff components during spring. According to the RCP 6.0 scenario, the significance of change in the Oka Basin water regime will increase substantially: only changes in winter surface runoff, as well as in the winter and summer–autumn groundwater flow by mid-century, will be statistically insignificant.

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