RESEARCH PAPER

CLIMATE CHANGE IMPACT ON WATER BALANCE COMPONENTS IN ARCTIC RIVER BASINS

Olga N. Nasonova[1*], Yeugeny M. Gusev[1], Evgeny Kovalev[1]
[1]Water Problems Institute of Russian Academy of Sciences, Gubkina St. 3, Moscow, 119333, Russian Federation
***Corresponding author:** olniknas@yandex.ru
Received: February 23rd, 2021 / Accepted: November 11th, 2022 / Published: December 31st, 2022
https://DOI-10.24057/2071-9388-2021-144

ABSTRACT. Climate change impact on the water balance components (including river runoff, evapotranspiration and precipitation) of five Arctic river basins (the Northern Dvina, Taz, Lena, Indigirka, and MacKenzie), located in different natural conditions, was investigated using a physically-based land surface model SWAP and meteorological projections simulated at half-degree spatial resolution by five Global Climate Models (GCM) for four Representative Concentration Pathways (RCP) scenarios from 2005 to 2100. After the SWAP model calibration and validation, 20 projections of changes in climatic values of the water balance components were obtained for each river basin. The projected changes in climatic river runoff were analyzed with climatic precipitation and evapotranspiration changes. On average, all rivers' water balance components will increase by the end of the 21st century: precipitation by 12-30%, runoff by 10–30%, and evapotranspiration by 6-47% depending on the river basin. The partitioning of increment in precipitation between runoff and evapotranspiration differs for the selected river basins due to differences in their natural conditions. The Northern Dvina and Taz river runoff will experience the most negligible impact of climate change under the RCP scenarios. This impact will increase towards eastern Siberia and reach a maximum in the Indigirka basin. Analysis of the obtained hydrological projections made it possible to estimate their uncertainties by applying different GCMs and RCP scenarios. On average, the contribution of GCMs to the uncertainty of hydrological projections is nearly twice more significant than the contribution of scenarios in 2006–2036 and decreases over time to 1.1-1.2 in 2068–2099.

KEYWORDS: climate change, land surface model, Arctic rivers, hydrological projections, RCP scenarios

CITATION: Nasonova O. N., Gusev Ye. M., Kovalev E. E. (2022). Climate Change Impact On Water Balance Components In Arctic River Basins. Geography, Environment, Sustainability, 4(15), 148-157
https://DOI-10.24057/2071-9388-2021-144

ACKNOWLEDGEMENTS: The authors are grateful to the organizers of the International project ISIMIP for providing global data sets on meteorological data and land surface parameters. This study was carried out within the framework of the State Assignment theme of WPI RAS (№ FMWZ-2022-0001).

Conflict of interests: The authors reported no potential conflict of interest.

INTRODUCTION

It is generally accepted that the pan-Arctic basin will be subject to major changes due to projected global warming, which is expected to be most significant in northern regions, resulting in an increase of air temperature, precipitation and snowmelt. This can lead to significant changes in heat and water balances of drainage area of Arctic rivers, which, in turn, will affect the annual volume of river runoff, as well as the shape and timing of runoff hydrographs. The influence of northern river runoff on the Arctic Ocean is very great. Thus, the influx of fresh water to the Arctic Ocean by means of runoff from the drainage area of the pan-Arctic basin represents about 50% of its net flux (Barry and Serreze, 2000). Taking into account the role of the rivers of the pan-Arctic basin in the transfer of heat, sediment, nutrients and pollutants to the north, changes in the environment caused by climate change, even at low latitudes, can have a significant impact on the freshwater balance of the Arctic Ocean, on the influx the above substances, on sea ice formation, and, ultimately, on the thermohaline circulation and global climate. That is why investigation of the impact of global warming on the hydrological cycle and the dynamics of its components in the Arctic region is very important and relevant.

There are a lot of papers devoted to assessment of changes in Arctic river runoff in the 21st century (see review in (Dai 2016; Gelfan et al. 2022)). They are carried out by global and regional Hydrological Models (HMs) and Land Surface Models (LSMs) using projections of meteorological forcing data from Global Climate Models (GCMs) to project changes in river runoff (e.g., Gusev et al. 2013, 2018; Arnell and Lloyd-Hughes 2014; Gelfan et al. 2017; Gosling et al. 2017; Krysanova and Hattermann 2017; Bring et al. 2017, Nasonova et al. 2019, 2021). However, there are much more studies, which use runoff projections simulated by GCMs (Georgiady and Milyukova 2006; Kattsov et al. 2007; Kislov et al. 2011; Khon and Mokhov 2012; Shkolnik et al. 2014; Koirala 2014; Dobrovolski 2014; Georgievsky and Golovanov 2019) and analyze them for different regions of the globe with or without identifying Arctic river basins. Studies of possible changes in river runoff differ in methods, models, climatic scenarios, climatic periods, and areas used. However, in general, recent studies project an increase in Arctic river runoff by 10-50%, depending on the location of modeling object and climatic scenario.

During the last decade we also performed scenario projections of changes in water balance components for Arctic river basins using our land surface model SWAP (Soil Water – Atmosphere – Plants) and different families of greenhouse gas emission scenarios: IS95, SRES (Special Report on Emissions Scenarios) and RCP (Representative Concentration Pathways). The IS92 family was prepared for the IPCC Second Assessment Report, published in 1995. SRES scenarios were used in the IPCC Third (TAR) and Fourth Assessment Reports (AR4), published in 2001 and 2007, respectively. SRES was replaced by RCP prepared for the IPCC Fifth Assessment Report. The methodological approaches used for the constructions of the above families of scenarious, as well as description and analysis of the scenarious are given in Semenov and Gladilshchikova (2022).

In our earlier studies, we carried out hydrological projections up to the 2060s for the Northern Dvina River basin using SWAP, IS92 scenarios and climate scenario generator MAGICC/SCENGEN, which allowed us to obtained meteorological projections for the ensemble of 16 GCMs (Gusev and Nasonova 2014). The same technique, but with SRES emission scenarios (A1, A2, B1, and B2), was applied to project changes in the water balance components for the Northern Dvina, Olenek, Indigirka, Lena and Ob'-Irtysh basins (Gusev and Nasonova 2014; Gusev et al. 2014, 2016b, 2019a).

The latest RCP scenarios we applied for projecting runoff for the Indigirka, Northern Dvina and Kolyma rivers in (Nasonova et al. 2018). In so doing, meteorological forcing data to drive the SWAP model were simulated by GCM INMCM4.0 for RCP4.5 and RCP8.5 by the end of the 21st century. Five different procedures were used for bias-correction of GCM meteorological outputs to reveal their contribution to the uncertainty in runoff projections.

Participation in the International Inter-Sectoral Impact Model Intercomparison Project, phase 2 (ISI-MIP2) (Krysanova and Hattermann 2017), initiated our implementation of a number of studies aimed at modeling and projecting runoff for 11 river basins located in different regions of the globe and suggested within the framework of the project (e.g., Gusev et al. 2018; Nasonova et al. 2021). In these studies, the projections of forcing data by the end of the 21st century were simulated by five GCMs for four RCP scenarios. It should be noted that there were only two Arctic rivers (the Lena and MacKenzie) among 11 ones.

The present work is a continuation of our ISIMIP-related studies. We will use the same RCP scenarios and GCMs' meteorological outputs to force the SWAP model to simulate hydrological projections. However, here, five Arctic rivers will be involved and the main emphasis will be on the following issues: (1) on the analysis of all components of the water balance, i.e. river runoff projections will be analysed in relation to projected precipitation and evapotranspiration; (2) to identify the causes and patterns of projected changes and find out where the projected changes in the water balance components will be the largest and why; (3) to get more insight in uncertainties of hydrological projections sourced from application of different GCMs and RCP scenarios in order to reveal where the uncertainties are the highest and why.

MATERIALS AND METHODS

As mentioned above, five Arctic river basins were selected for modeling (Fig. 1). Four of them (the Northern Dvina, Taz, Lena, and Indigirka) are situated in Russia, while the MacKenzie is in North America. Some characteristics of the basins are given in Table 1.

The choice of Russian basins was motivated by the fact that they are situated in very contrasting natural conditions. Thus, when moving from the westernmost basin to the east, the climate becomes more and more severe: from temperate in the Northern Dvina basin to subarctic and arctic in the Indigirka basin. The continentality of the climate also increases in the same direction. As a result, the long-term mean annual air temperature, averaged over each basin, decreases from 0.8°C for the Northern Dvina to -5.4°C for the Taz, to -10.2°C for the Lena and to -17.6°C for the Indigirka (Table 1). The Pole of Cold of the Northern Hemisphere with a recorded absolute minimum of air temperature equalled to -67.7°C is located in the Indigirka basin (in Oymyakon). Precipitation also decreases eastward with increasing continentality from 655 mm/year for the Northern Dvina basin to 250 mm/year for the Indigirka; the runoff ratio increases from 0.44 to 0.65 (Table 1). Seasonally frozen soils in the Northern Dvina basin are replaced by permafrost in the other basins.

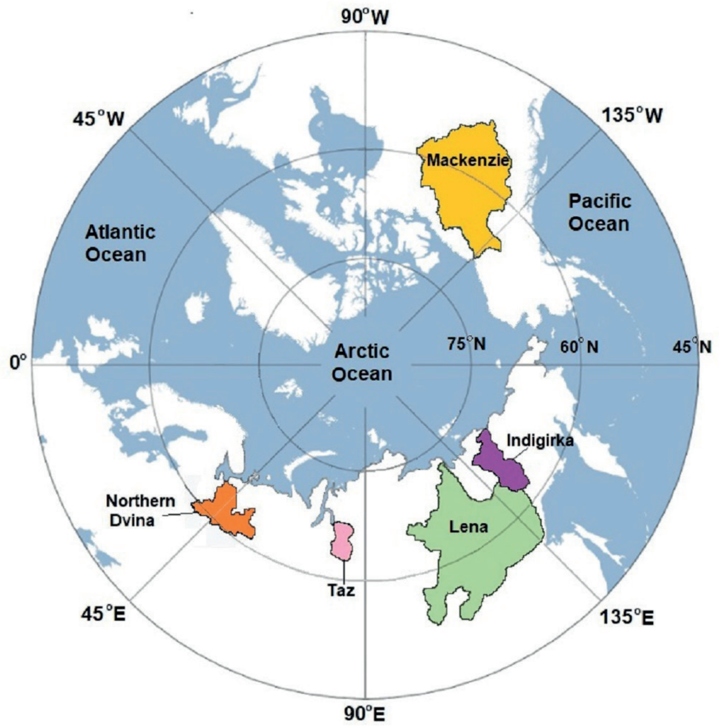

Fig. 1. Distribution of the river basins in the Arctic used in this study

It seemed interesting to complete the picture with the MacKenzie River, which stands apart from the other rivers. Like the Lena River, it is mostly located in the temperate and subarctic zones, but its long-term mean annual air temperature is higher (-4.3°C versus -10.2°C) and permafrost underlies about ¾ of the basin area, while the Lena basin is fully in the permafrost zone. In addition, the MacKenzie has the lowest runoff ratio (0.39) among the rivers (Table 1).

For model simulations, the basins were presented as a set of regular grid cells (with a spatial resolution of 0.5°x0.5° in latitude and longitude) connected by a river network. The number of calculational grid cells for the basins varies from 88 for the Taz River to 1668 for the Lena River (Table 1).

Model

Simulation of river runoff and evapotranspiration for the selected river basins was performed by the spatially-distributed physically-based model SWAP (Gusev and Nasonova 2010). SWAP belongs to the class of land surface models which differ from hydrological models in that they treat not only hydrological processes, but also heat and radiation exchange at the land surface – atmosphere interface. Besides, LSMs require more forcing data including incoming shortwave and longwave radiation, wind speed and air pressure along with precipitation, air temperature and humidity which usually force hydrological models. Output data can reach several dozens variables including different state variables, as well as radiation, heat, and water fluxes. To obtain river runoff at the basin outlet a river routing model was inserted into the SWAP model.

Description of the model and its successful validation performed for experimental sites and for catchments and river basins of different size on a long-term basis and under different natural conditions (from arid to humid and from non-frozen soils to seasonally frozen ones and permafrost) were summarized in (Gusev and Nasonova 2010). Comparison with hydrological models has shown that the LSM SWAP can reproduce river runoff as good as HMs (Nasonova 2011; Nasonova et al. 2009). Taking into account the purpose of the given paper, it should be noted that SWAP has been extensively validated against observed streamflow of northern Russian rivers: the Mezen' (Gusev et al. 2008); Pechora (Gusev et al. 2010); Ponoi, Onega, and Tuloma (Gusev et al. 2011a); Northern Dvina (Gusev et al. 2011b); Olenek and Indigirka (Gusev et al. 2013); Kolyma (Gusev et al. 2015a), Nadym, Pur, and Taz (Gusev et al. 2015b); Lena (Gusev et al. 2016a), and Ob' with Irtysh (Gusev et al. 2019b). The results of validation proved the ability of SWAP to model hydrological processes at high latitudes and in permafrost regions quite adequately.

Meteorological forcing data

Forcing data to drive the SWAP model include incoming longwave and shortwave radiation, air temperature and humidity, precipitation, wind speed, and air pressure. The data were provided within the framework of the ISI-MIP2, in which we participated with SWAP.

For hydrological projections, daily values of forcing data were simulated by five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M) for each of four RCP scenarios (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) for the period of 2006–2099. Large numbers in scenarios abbreviations correspond to more aggressive anthropogenic scenarios due to increased emissions of greenhouse gases into the atmosphere and weak measures to limit their release. In addition to the prognostic values, the values of meteorological forcing data simulated by the five GCMs for the historical period (1961-2005) were also provided. They were needed to simulate river runoff using SWAP for the historical period.

Since meteorological outputs from GCMs usually suffer from systematic errors, they were subject to a post-processing bias-correction to the WATCH data within the framework of the ISI-MIP2 project. A detailed description of the bias-correction technique can be found in (Hempel et al. 2013). In so doing it was assumed that the WATCH data, based on ERA-40 reanalysis and hybridized with monthly values of ground-based measurements taken from the Global Precipitation Climatology Center (GPCC) and the Climatic Research Unit (CRU of University of East England) data sets (Weedon et al. 2011), are close to real meteorology.

The WATCH data were also used for calibration and validation of the SWAP model. For this purpose, daily values of meteorological forcing data for the period of 1969–2001 were derived from the WATCH data set for each calculation grid cell of the selected basins.

Model parameters, their calibration and validation

In addition to the forcing data, SWAP needs the land surface parameters for each calculational grid cell. A priori values of vegetation parameters (vegetation class, leaf area index – LAI, albedo, roughness length, greenness fraction, vegetation height, rooting depth) were taken from the global ECOCLIMAP data set (Champeaux et al. 2005), which includes land surface parameters at 1 km spatial resolution. For model simulations, parameter values were aggregated to a half-degree resolution.

A priori soil parameters (porosity, field capacity, wilting point, hydraulic conductivity at saturation, soil matric potential at saturation and B-parameter in parameterisation by Clapp and Hornberger (1978)) were estimated using

Table 1. River basins used in this study with the number of calculational grid cells; gauge stations with coordinates; averaged over 1971-2000 air temperature *T*, precipitation *Pr*, river runoff *R* and runoff ratio *R/Pr*

River basin	Area, km²	Number of grid cells	Streamflow gauge station			*Tr*, °C	*P*, mm/yr	*R*, mm/yr	*R/Pr*
			Name	Latitude	Longitude				
Northern Dvina	348 000	248	Ust'-Pinega	64.13°N	42.17°E	0.8	665	295	0.44
Taz	100 000	88	Sidorovsk	66.60°N	82.28°E	-5.4	650	334**	0.52**
Lena	2 460 000	1668	Stolb	72.37°N	126.80°E	-10.2	384	201	0.52
Indigirka	305 000	243	Vorontsovo	69.58°N	147.35°E	-17.6	250	164*	0.65*
MacKenzie	1 660 000	1128	Arctic Red River	67.46°N	133.74°W	-4.3	435	171	0.39

*1970-1977, 1979-1991, 1993, 1994 (23 years); **1970-1979, 1982,1983,1987-1990,1994-1996 (18 years).

equations by Cosby et al. (1984) and data on soil texture from the ECOCLIMAP.

To improve the quality of hydrological modeling, a number of a priori model parameters, which have the greatest effect on runoff formation, were calibrated. The experience of working with the SWAP model has shown that the following seven parameters can be calibrated for the northern river basins: the hydraulic conductivity at saturation, the soil rooting depth, the soil column depth (from the soil surface to the depth of impermeable layer), snow-free surface albedo, fresh snow albedo, the Manning's roughness coefficient and the effective velocity of water movement in a channel network. For the first four parameters, the correction factors to a priori parameter values were calibrated.

Calibration was carried out against river runoff measured during 7-8 years at streamflow gauge stations (Table 1) located at the basin outlets. In so doing, the large basins of the Lena and Mackenzie rivers were divided into three parts and optimal values of model parameters were obtained for each of them.

Shuffled Complex Evolution method (SCE-UA) was used for automatic calibration (Duan et al. 1992). The objective function represented the Nash and Sutcliffe efficiency

$$NS = 1 - \frac{\sum_{\Omega} \left(x_{cal} - x_{obs}\right)^2}{\sum_{\Omega} \left(x_{obs} - \bar{x}_{obs}\right)^2} \tag{1}$$

where x_{cal} and x_{obs} are calculated and observed values of a variable x (here, monthly river runoff), Ω is a discrete sample set of the variable x.

The search of the maximum value of the objective function during calibration was carried out under the condition that the absolute value of the systematic error *Bias*, calculated as follows

$$Bias = \frac{\sum_{\Omega} \left(x_{cal} - x_{obs}\right)}{\sum_{\Omega} x_{obs}} \cdot 100\,\% \tag{2}$$

cannot exceed 5%.

The calibrated parameters were used for modeling river runoff for the selected basins using SWAP together with forcing data from WATCH and five GCMs. The modeled runoff for the historical period was compared with the available measured runoff at the basin outlets to validate the model.

Projecting changes in river runoff and their uncertainties

For the future period (2006-2099), daily values of river runoff and evapotranspiration were simulated by the SWAP model forced by each of 20 meteorological projections (5 GCMs X 4 RCP scenarios). Then annual values of the water balance components (river runoff – *R*, evapotranspiration – *E*, and precipitation – *Pr*) were calculated. For subsequent analysis, the prognostic period was divided into three parts: P1 (2006-2036), P2 (2037-2067) and P3 (2068-2099). The projected annual water balance components were averaged over each period to obtain their climatic values. Changes in the climatic values of each variable $\Delta X_{GCM,RCP,Pi}$ (*X*=*R*, *E*, *Pr*) obtained for each GCM, each RCP scenario, and prognostic period *Pi* (i=1, 2, 3) were calculated as the difference between the projected value $X_{GCM,RCP,Pi}$ and the historical one $X_{GCM,H}$ (simulated with the same GCM's forcing data and averaged over 1971-2005):

$$\Delta X_{GCM,RCP,Pi} = X_{GCM,RCP.Pi} - X_{GCM,H} \tag{3}$$

Relative changes were calculated as follows:

$$\Delta X_{GCM,RCP,Pi}\,\% = \frac{\Delta X_{GCM,RCP,Pi}}{X_{GCM,H}} \cdot 100\,\% \tag{4}$$

Thus, for each variable *X* and for each prognostic period, the ensembles of 20 values of $\Delta X_{GCM,RCP,Pi}$ and $\Delta X_{GCM,RCP,Pi}$% were obtained. After that ensemble mean value M and standard deviation STD were calculated. As it was shown in (Gelfan et al. 2017), the interval (M±1.96 STD) can be treated as the index of hydrological projection uncertainty caused by both the climate scenario variability and the climate model structural uncertainty.

Assessment of the contribution of uncertainties in RCP scenarios and GCMs to hydrological projection uncertainty

The obtained changes in the water balance components $\Delta X_{GCM,RCP,Pi}$ and $\Delta X_{GCM,RCP,Pi}$% allowed us to estimate the contribution of GCMs' structural uncertainty and RCP scenarios differences into the uncertainty of the hydrological projections. For this purpose, for each prognostic period and each river, the ranges of variability of ΔX as a difference between the maximum and the minimal values were estimated:

$$Range = \Delta X_{max} - \Delta X_{min} \tag{5}$$

If we use all 20 values of $\Delta X_{GCM,RCP,Pi}$ or $\Delta X_{GCM,RCP,Pi}$% for estimating the range ($Range_{GCM,RCP}$ or $Range_{GCM,RCP}$%), we will obtain uncertainty caused by both GCMs and RCP scenarios. Besides, we can calculate the variation ranges caused only (1) by a scatter among GCM's projections $Range_{GCM}$ (calculated for each scenario and then averaged over the scenarios) and (2) by a scatter due to different RCP scenarios $Range_{RCP}$ (calculated for each model and then averaged over the models). The former indicates the contribution of the climate model structural uncertainty into the hydrological uncertainty, while the latter is associated with the contribution of the climate scenario differences.

RESULTS AND DISCUSSION

Model validation

First of all the calibrated values of model parameters were used to simulate streamflow of the five rivers by the SWAP model using forcing data from WATCH. The results of simulation were compared with corresponding observations at streamflow gauge stations located at the basin outlets. The agreement between simulations and observations for each river basin was assessed on monthly basis using goodness-of-fit statistics such as the Nash-Sutcliffe coefficient of efficiency *NS* and systematic error *Bias*. The results of comparison are presented in Table 2.

As can be seen from Table 2, for the validation period, the worst results in terms of *Bias* were obtained for the Taz River: *Bias*=13.3%. This may be due to deterioration in the quality of measurements after 1979. Thus, there are no gaps in measurements for the calibration period, while for 1980-1996 31% of data are missing and after 1996 measurements are absent.

Fig. 2 shows the progress in SWAP streamflow simulations after calibration of the model parameters. As can be seen, for all rivers, hydrographs simulated by SWAP with calibrated parameters match the observed hydrographs much better than hydrographs simulated with a priori parameters. The worst agreement was obtained for the Lena River: *NS*=0.58 (Table 2). However, in this case,

Table 2. Systematic error (Bias) and Nash-Sutcliffe coefficient of efficiency (NS) for monthly values of streamflow simulated by the SWAP model with optimized parameters for the calibration and validation periods

River	Streamflow gauge station	Calibration period				Validation period			
		Years		*Bias*, %	*NS*	Years		*Bias*, %	*NS*
		Period	Number of years			Period	Number of years		
Northern Dvina	Ust'-Pinega	1973-1979	7	2.67	0.89	1971-2001	31	2.0	0.87
Taz	Sidorovsk	1973-1979	7	0.43	0.93	1971-1996	26	13.3	0.84
Lena	Stolb	1972-1979	8	0.18	0.68	1970-2001	32	-0.49	0.58
Indigirka	Vorontsovo	1973-1979	7	4.60	0.93	1971-1994	24	-2.8	0.89
MacKenzie	Arctic Red River	1973-1980	8	-1.13	0.83	1970-2001	32	4.01	0.76

the systematic error is negligible (*Bias*≈-0.5%) that is much more important for the purpose of the paper, since we will operate with annual values rather than hydrographs.

The results of the comparison led to the conclusion that the obtained optimal values of model parameters can be applied for modeling streamflow for the above rivers.

Before proceeding to hydrological projections until the end of the 21st century using meteorological projections from the aforementioned five GCMs, the simulations with the obtained optimal parameters were performed by SWAP for the historical period (1961-2005) in order to find out how adequately river runoff is reproduced with meteorological outputs from the global models. The simulated annual runoff for each river was compared with observations. Fig. 3 shows comparison of climatic (averaged over historical period) annual values of simulated runoff in comparison with corresponding observed runoff for each river and for each GCM's forcing data.

As can be seen from Fig. 3, the simulated climatic runoff is overestimated, despite the fact that meteorological data from GCMs were bias-corrected to WATCH data (which were used for obtaining optimal parameters). This allowed us to conclude that the meteorological outputs from the above GCMs can be used for hydrological projections, however, to eliminate the impact of systematic errors in the results

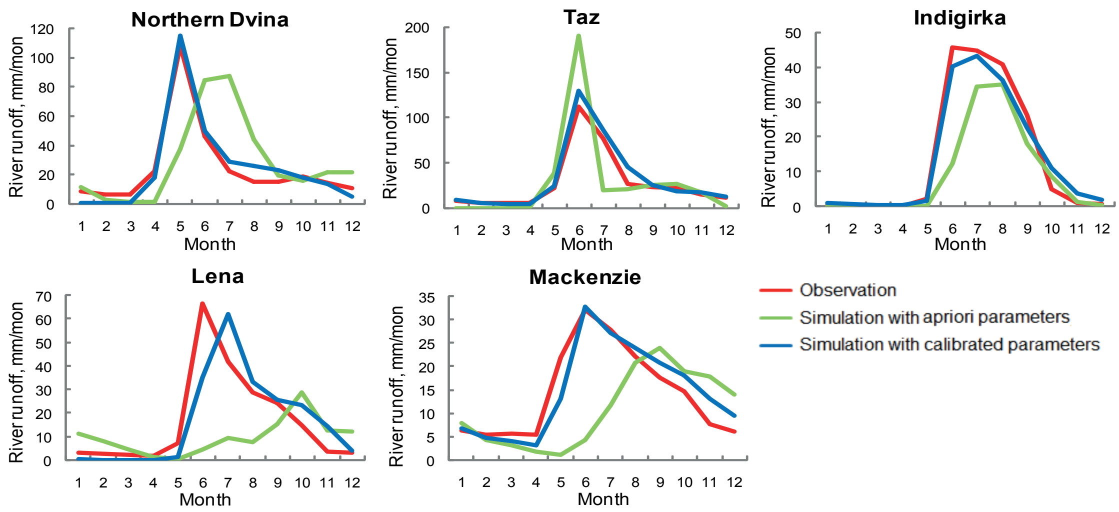

Fig. 2. Averaged over the calculational period monthly hydrographs measured at the river basin outlets and simulated by SWAP with a priori and calibrated parameters

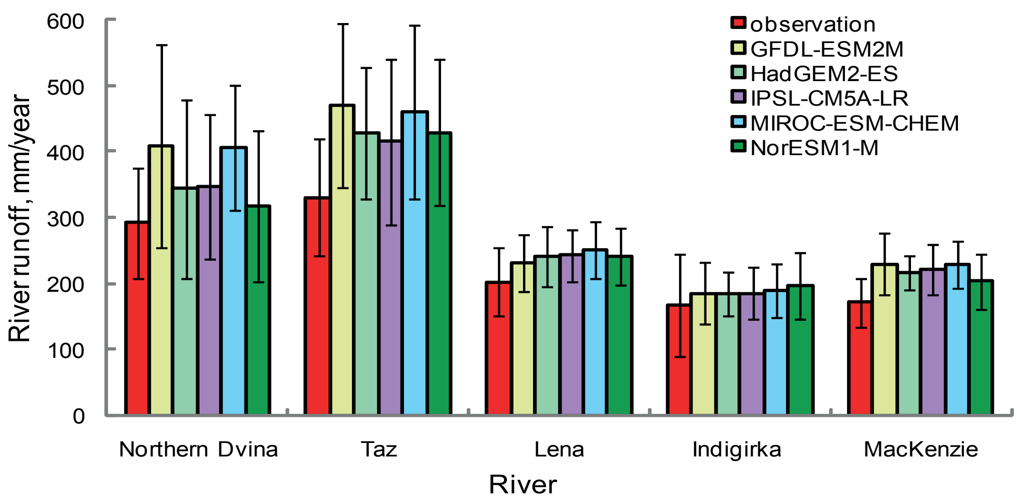

Fig. 3. Climatic annual river runoff observed at the basin outlets and simulated by SWAP driven by meteorological forcing data from 5 GCMs. Vertical bars show the ranges of variability of annual runoff corresponding to MEAN±1.96 STD

of simulations the projected changes $\Delta X_{GCM}=X_{GCM,Pi}-X_{GCM,H}$ in the water balance components will be considered rather than the projected values.

Hydrological projections

The projected changes in annual values of climatic runoff ΔR and precipitation ΔPr calculated by Eqs. (3) and (4) and averaged over the ensemble of five GCMs and four climatic scenarios (i.e., representing the ensemble mean M) are presented in Fig. 4. They are shown for three climatic periods and five rivers. All changes are positive and increase in time, being the largest during the third period P3. For P3, relative changes in runoff range from 10% for the Taz River up to 30% for the Indigirka (Fig. 4a); relative changes in precipitation are in the range of 12–30%, being the lowest for the Mackenzie River and the largest for the Indigirka (Fig. 4c).

In Fig. 4, bars correspond to the intervals of uncertainty in the projected ΔR and ΔPr caused by both the GCMs structural uncertainty and the RCP scenario differences. The largest uncertainty in relative ΔR was found for the Indigirka River. This can be explained by the largest variability of the projected changes in climatic precipitation for this river.

It is interesting to analyze the absolute changes in climatic river runoff (Fig. 4b) in comparison with the absolute changes in precipitation (Fig. 4d) for the third period. For analysis, it is convenient to divide the rivers into two groups: (1) the Taz, Northern Dvina, and MacKenzie with similar ΔR equaled to 44, 42 and 39 mm/year versus large differences in ΔPr equaled to 137, 100 and 55 mm/year, respectively; (2) the Lena and Indigirka with 58 and 67 mm/year increment in runoff versus similar ΔPr equaled to 81 and 79 mm/year, respectively. Both cases can be explained with the help of Fig. 5, which shows changes in forcing data, namely, precipitation and air temperature averaged over each climatic period and for each river basin.

Fig. 5a illustrates how the projected ΔPr partitions between the increments in runoff ΔR and evapotranspiration ΔE. Fig. 5b depicts the projected increase in air temperature ΔT, which leads to an increase in evapotranspiration for all rivers and all periods (Fig. 5a). However, the value of ΔE can be different despite of the same ΔT due to different increases in potential evapotranspiration. As it was obtained in our global simulations with the same models and climatic scenarios, the increase in potential evapotranspiration in 2068-2099 in the areas of the Lena, Indigirka and MacKenzie river basins is much lower than in the Northern Dvina and Taz basins (Nasonova et al., 2021, Fig. 5e). That is why for the Northern Dvina and Taz, ΔE is much larger than for the other rivers.

Contribution of GCMs and climatic scenarios to hydrological uncertainty

Fig. 6 shows projected changes in climatic annual runoff for five rivers and for three climatic periods. In the upper panels, the projections are averaged over the GCMs, therefore, differences between them are due to different RCP scenarios and can be considered as uncertainties sourced from climatic scenarios. For the Northern Dvina (Fig. 6d) and Taz (Fig. 6e), these uncertainties are the lowest. For the other rivers, the uncertainties grow with time and reach the highest values for the Indigirka River; the projected increase in river runoff is minimal for the RCP2.6 scenario and maximum for the RCP8.5 one.

In the bottom panels of Fig. 6, the projections are averaged over the climatic scenarios, hence the scatter among the projected values is caused by differences in the meteorological forcing data from the GCMs and therefore it can be treated as uncertainty sourced from differences in the GCMs structure. This uncertainty also grows with time for all rivers except the Northern Dvina and Taz. In general, it is also greater than the uncertainty caused by RCP scenarios. Again, the Indigirka River has the largest uncertainty (Fig. 6f).

Thus, the obtained results allow us to conclude that the contribution of GCMs to the uncertainties in Arctic river runoff projections is larger than the contribution of the RCP climatic scenarios. This is also confirmed by Fig. 7.

Fig. 7 shows mean variation ranges of projected changes in climatic annual river runoff and precipitation due to differences in GCM forcings, RCP scenarios, and both GCMs and scenarios: $Range_{GCM}$, $Range_{RCP}$ and $Range_{GCM/RCP}$, respectively. They represent uncertainties in hydrological projections caused, respectively, by differences in climatic scenarios, by structural uncertainties in GCMs, and by joint influence of scenarios and GCMs. The ranges were averaged over five rivers for each prognostic period and sorted in increasing order of $Range_{GCM/RCP}$. In general, uncertainties in the projected relative changes in river runoff are somewhat greater than in precipitation. The results presented in Fig. 7

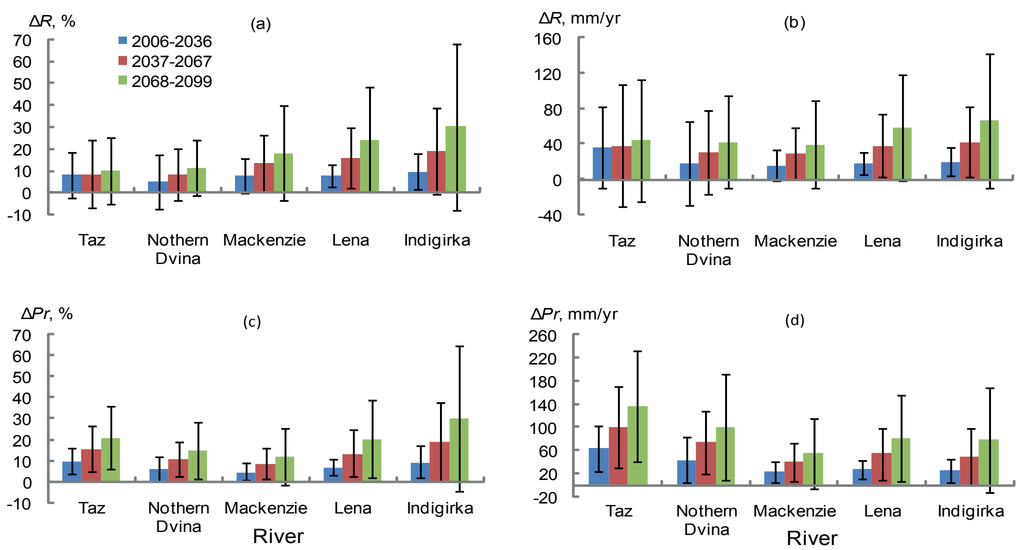

Fig. 4. The projected multimodal and multiscenario changes in (a, b) annual river runoff and (c, d) precipitation, averaged over three climatic periods, and their uncertainties (vertical bars) sourced from different GCMs and RCP-scenarios. Bars are the intervals (M±1.96×STD)

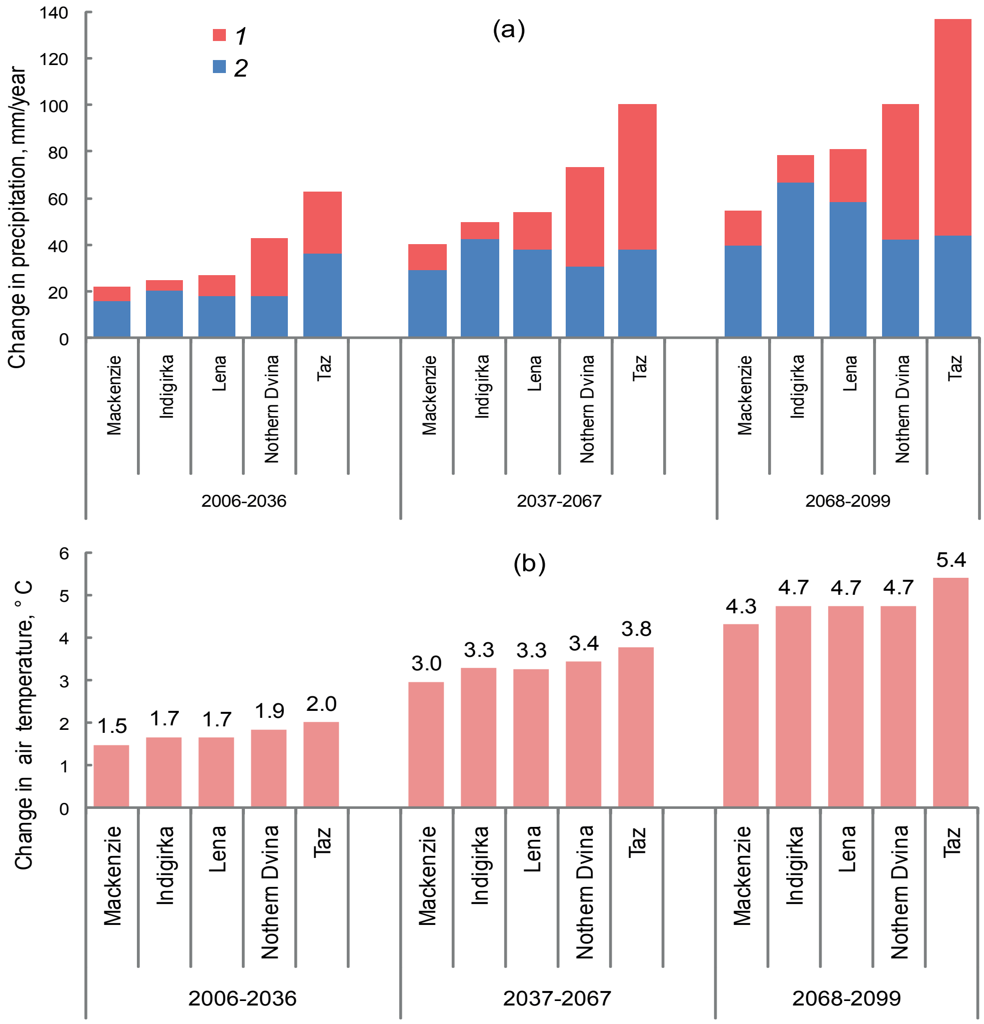

Fig. 5. The projected mean changes in climatic annual (a) precipitation (with partitioning between evapotranspiration – *1* and runoff – *2*) and (b) air temperature

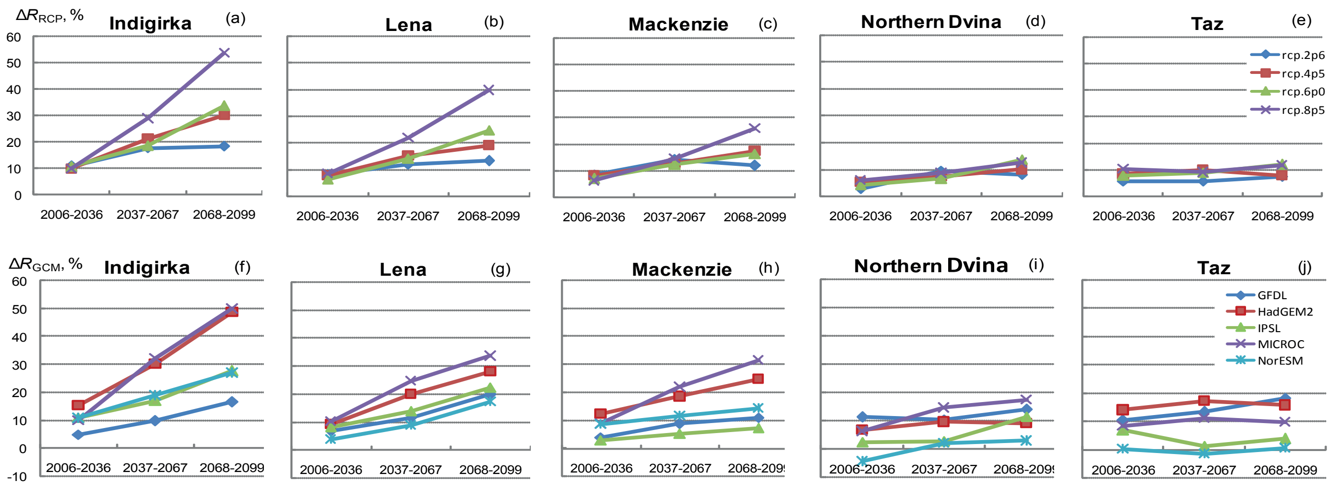

Fig. 6. The projected relative changes in climatic annual river runoff for three climatic periods: (a-e) averaged over five GCMs, (f-j) averaged over four climatic RCP-scenarios

confirm that all types of uncertainties grow with time; the contribution of various RCP scenarios to the uncertainty of precipitation and river runoff is less than that of GCMs, however, it is increasing by the end of the 21st century. Thus, the ratio of $Range\%_{GCM}$ to $Range\%_{RCP}$ decreases with time: for precipitation, from 1.9 for P1 to 1.1 for P3, and for runoff, from 2.2 for P1 to 1.2 for P3 period. As seen, in the third period the GCMs and scenarios make nearly the same contribution to the uncertainty of projected changes in precipitation (Fig. 7 b, d), while the contribution of scenarios is still less in the case of runoff projections (Fig. 7 a, c).

Discussion

The projected changes in Arctic river runoff are in a good agreement with the results found in literature. Thus, in (Bring et al. 2017), simulated by macro-scale hydrological model WBM multimodal and multiscenario (averaged over six GCMs and three RCP scenarios excluding the lowest-emission RCP2.6 scenario) change in annual river discharge for 2061-2090 compared to 1961-1990 is within the range of 0-25% in the region of the Northern Dvina and Taz basins, 25-50% for the most part of Lena, more 50% in the location

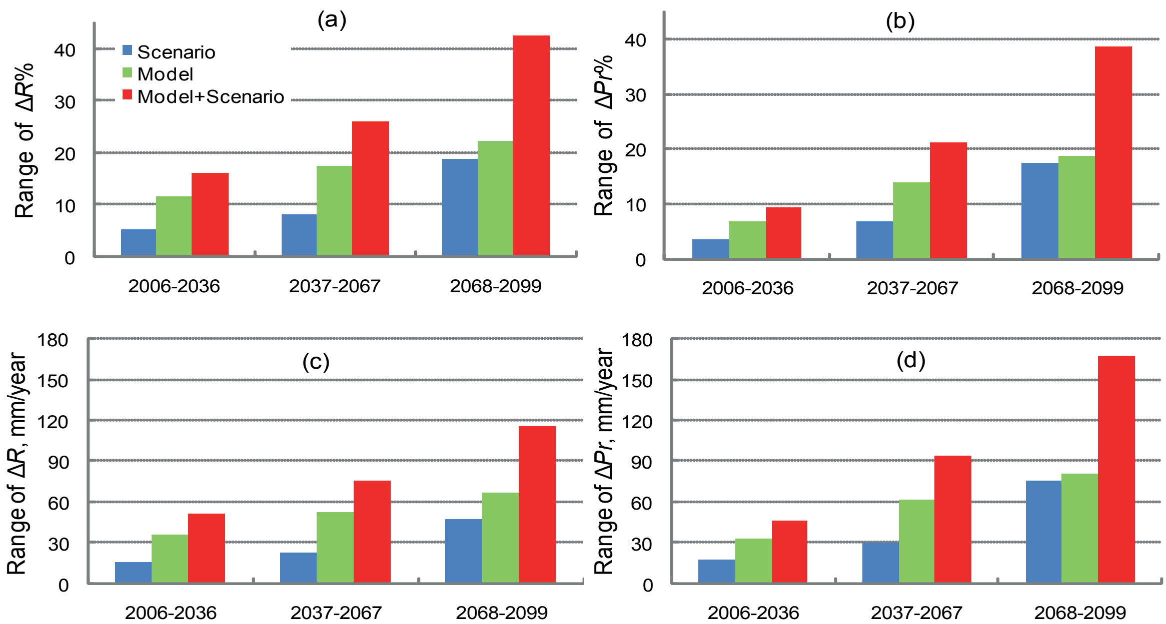

Fig. 7. Averaged over 5 river basins variation ranges of projected changes in climatic values of annual (a, c) runoff and (b, d) precipitation caused by differences in the RCP scenarios (blue), GCMs (green) and both scenarios and models (red)

of Indigirka and mostly 0-25% in the area of MacKenzie basin (Bring et al. 2017, Fig. 3). If we also exclude RCP2.6 scenario, our ensemble-averaged estimates of changes in river runoff are 10, 12, 20, 28 and 39% for the Taz, Northern Dvina, MacKenzie, Lena and Indigirka, respectively. This means that they fall within the above intervals and the directions of increase in the projected changes also coincide. They also coincide with the results published in (Georgievsky and Golovanov 2019), according to which positive changes (for 2041-2060 under RCP4.5 and RCP8.5 scenarios) in annual runoff are projected for the entire pan-Arctic basin of Russia, reaching the highest values in the north-eastern part of Siberia (including, in particular, the Lena and Indigirka basins).

As to uncertainties, our conclusion about the contribution of climate model structural uncertainty and differences in emission scenarios to the overall hydrological uncertainty is consistent with previous studies. The lowest uncertainties in runoff projections were obtained for the Northern Dvina and Taz rivers, higher uncertainties for the Mackenzie and Lena, and the highest ones for the Indigirka. This can be explained by the fact that meteorological outputs from GCMs are more reliable for the East-European and West-Siberian plains of Russia (Kislov et al. 2011). In (Nasonova et al. 2018), the same conclusion was made for the outputs from GCM INMCM4.0, which were of good quality for the Northern Dvina River basin and rather poor for the Indigirka and Kolyma basins.

CONCLUSIONS

Calibration of the most influencing parameters against measured river runoff resulted in significant improvement of SWAP performance with respect to goodness-of-fit statistics and the shape of hydrograph. For the calibration period, absolute value of *Bias* did not exceed 5% for all rivers, *NS* for monthly runoff varied from 0.68 to 0.93 (median value = 0.89). For the validation period, absolute *Bias* did not exceed 3% for 4 rivers, while *Bias*=13.3% for the Taz river, NS varied from 0.58 to 0.89 (median value = 0.84). Hydrological projections up to the end of the 21st century were carried out with the help of SWAP driven by meteorological projections simulated by five GCMs for four climatic scenarios of the RCP family. On the average, for all rivers, precipitation will increase by the end of the 21st century by 12% (Mackenzie) - 30% (Indigirka), runoff will increase by 10% (Taz) – 30% (Indigirka), evapotranspiration by 6% (Mackenzie) - 47% (Taz).

The largest increase in river runoff (averaged over five GCMs) was obtained for the RCP8.5 scenario by the end of 21st century: 12% for the Taz and Northern Dvina rivers, 26% for the Mackenzie, 40% for the Lena and 54% for the Indigirka.

Thus, the runoff of the Northern Dvina and Taz rivers will experience the least impact of climate change under the RCP scenarios, this impact will increase towards eastern Siberia and reach a maximum in the Indigirka basin.

Analysis of the uncertainties in the projected changes in the water balance components has shown that:

- all types of uncertainties increase by the end of the 21st century;

- on the territory of Russia, the uncertainties increase eastward from the lowest values for the Northern Dvina and Taz rivers to the largest values for the Indigirka River;

- the uncertainties in river runoff are in a good agreement with uncertainties in precipitation;

- on the average, the contribution of GCM structural uncertainty to the uncertainty of hydrological projections is nearly twice larger than the contribution of differences in emission scenarios in 2006-2036 and decreases over time to 1.1-1.2 in 2068-2099.

REFERENCES

Arnell N.W. and Lloyd-Hughes B. (2014). The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. Climatic change, 122, 127–140, DOI: 10.1007/s10584-013-0948-4.

Barry R.G. and Serreze M.C. (2000). Atmospheric component of the Arctic Ocean freshwater balance and their interannual variability. In: The Freshwater Budget of the Arctic Ocean (Eds: Lewis E.L., Jones E.P., Lemke P., Prowse T.D., and Wadhams P.). New York: Springer, 45-56, ISBN-13: 978-0792364405.

Bring A., Shiklomanov A., and Lammers R.B. (2017). Pan-Arctic river discharge: Prioritizing monitoring of future climate change hot spots. Earth's Future, 5, 72-92, DOI: 10.1002/2016EF000434.

Champeaux J.L., Masson V., and Chauvin F. (2005). ECOCLIMAP: a global database of land surface parameters at 1 km resolution. Meteorol. Appl., 12, 29-32, DOI: 10.1017/S1350482705001519.

Clapp R.B. and Hornberger G.M. (1978). Empirical equations for some soil hydraulic properties. Water Resour. Res., 14(4), 601–604, DOI: 10.1029/WR014i004p00601.

Cosby B., Hornberger G., Clapp R., and Ginn T. (1984). A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. Water Resour. Res., 20, 682-690, DOI: 10.1029/WR020i006p00682.

Dai A. (2016). Historical and future changes in streamflow and continental runoff: A review In: Tang Q. and Oki T., eds., Terrestrial Water Cycle and Climate Change: Natural and Human-Induced Impacts, American Geophysical Union, Washington, D.C., 17-37, ISBN: 978-1-118-97176-5.

Dobrovolski S.G. (2014). Assessment of the statistical significance of global changes in the annual river runoff in XXI century due to possible anthropogenic warming of climate. Water Resources, 41(6), 728–737, DOI: 10.1134/S0097807814060049.

Duan Q., Sorooshian S., and Gupta V.K. (1992). Effective and efficient global optimization for conceptual rainfallrunoff models. Water Resour. Res., 28(4), 1015-1031, DOI:10.1029/91WR02985.

Gelfan A.N., Gusev E.M., Kalugin A.S., Krylenko I.N., Motovilov Yu.G., Nasonova O.N., Millionschikova T.D., and Frolova N.L. (2022). Runoff of Russian rivers under current and projected climate change: A review 2. Climate change impact on the water regime of Russian rivers in the XXI century. Water Resources, 22(3), 1-16.

Gelfan A., Gustafsson D., Motovilov Yu., Arheimer B., Kalugin A., Krylenko I., and Lavrenov A. (2017). Climate change impact on the water regime of two great Arctic rivers: modeling and uncertainty issues. Climatic Change, 141, 499-515, DOI: 10.1007/s10584-016-1710-5.

Georgiady A.G. and Milyukova I.P. (2006). River runoff within Lena river basin in conditions of probable global climate warming. Computational technologies, 11(2), 166-174 (in Russian with English summary).

Georgievsky M.V. and Golovanov O.F. (2019). Forcasting changes in river water resources of Russian Federation based on CMIP5 runoff data. Vestnik of Saint Petersburg University. Earth Sciences, 64(2), 206-218, (in Russian with English summary), DOI: 10.21638/spbu07.2019.203.

Gosling S.N., Zaherpour J., Mount N.J., Hattermann F.F., Dankers R., Arheimer B., Breuer L., Ding J., Haddeland I., Kumar R., Kundu D., Liu J. van Griensven A., Veldkamp T.I.E., Vetter T., Wang X., and Zhang X. (2017). A comparison of changes in river runoff from multiple global and catchment-scale hydrological models under global warming scenarios of 1°C, 2°C and 3°C. Climatic Change, 141, 577-595, DOI:10.1007/s10584-016-1773-3.

Gusev E.M. and Nasonova O.N. (2013). A technique for scenario prediction of changes in water balance components in northern river basins in the context of possible climate change. Water Resources, 40(4), 426-440, DOI: 10.1134/S0097807813040040.

Gusev Ye.M. and Nasonova O.N. (2014). Application of a technique for scenario prediction of climate change impact on the water balance components of northern river basins. J. Hydrol. Hydromech., 62(3), 197-208, DOI: 10.2478/johh-2014-0025.

Gusev E.M. and Nasonova O.N. (2010). Modeling heat and water exchange of the land surface and atmosphere. Moscow: Nauka (in Russian), ISBN 978-5-02-036958-0.

Gusev E.M., Nasonova O.N., and Dzhogan L.Ya. (2011a). Modeling river runoff in northwestern Russia with the use of land surface model SWAP and global databases. Water Resources, 38(5), 571-582, DOI: 10.1134/S0097807811050101.

Gusev E.M, Nasonova O.N, and Dzhogan L.Y. (2016a). Physically based modeling of many-year dynamics of daily streamflow and snow water equivalent in the Lena R. basin. Water Resources, 43(1), 21-32, DOI: 10.1134/S0097807816010085.

Gusev E.M., Nasonova O.N., and Dzhogan L.Y. (2015a). Physically based simulating long-term dynamics of diurnal variations of river runoff and snow water equivalent in the Kolyma River basin. Water Resources, 42(6), 834-841, DOI: 10.1134/S0097807815060056.

Gusev E.M., Nasonova O.N., and Dzhogan L.Y. (2010). Reproduction of Pechora runoff hydrographs with the help of a model of heat and water exchange between the land surface and the atmosphere (SWAP). Water Resources, 37(2), 182-193, DOI: 10.1134/S0097807810020065.

Gusev E.M., Nasonova O.N., and Dzhogan L.Y. (2016b). Scenario prediction of changes in water balance components in the Lena basin in the context of possible climate changes. Water Resources, 43(5), 754-765, DOI: 10.1134/S0097807816050079.

Gusev E.M., Nasonova O.N., Dzhogan L.Ya., and Aizel' G.V. (2013). Modeling Streamflow of the Olenek and Indigirka Rivers Using Land Surface Model SWAP. Water Resources, 40(5), 535-543, DOI: 10.1134/S0097807813030056.

Gusev E.M., Nasonova O.N., Dzhogan L.Y., and Ayzel G.V. (2014). Scenario prediction of changes in water balance components of the Olenek and Indigirka rivers in the context of possible climate change in the region of the republic of Sakha (Yakutia). Water Resources, 41(6), 748-762, DOI: 10.1134/S0097807814030099.

Gusev E.M., Nasonova O.N., Dzhogan L.Y., and Ayzel G.V. (2015b). Simulating the formation of river runoff and snow cover in the northern-west Siberia. Water Resources, 42(4), 460-467, DOI: 10.1134/S0097807815040065.

Gusev E.M., Nasonova O.N., Dzhogan L.Ya., and Kovalev E.E. (2011b). Northern Dvina runoff simulation using land-surface model SWAP and global databases. Water Resources, 38(4), 470-483. DOI: 10.1134/S0097807811030043.

Gusev E. M., Nasonova O. N., Dzhogan L. Ya., and Kovalev E. E. (2008). The Application of the Land Surface Model for Calculating River Runoff in High Latitudes. Water Resources. 35(2), 171-184, DOI: 10.1007/s11268-008-2005-7.

Gusev E.M., Nasonova O.N., Kovalev E.E, and Ayzel' G.V. (2018). Possible Climate Change Impact on River Runoff in the Different Regions of the Globe. Russian Meteorology and Hydrology, 43(6), 397-403, DOI: 10.3103/S1068373918060079.

Gusev E.M., Nasonova O.N., Shurkhno E.A., and Dzhogan L.Ya. (2019a). Scenario Forecasting of Changes in Water Balance Components in the Ob–Irtysh Basin in the Context of Possible Climate Change. Water Resources, 46(5), 647-658. DOI: 10.1134/S0097807819050099.

Gusev E.M., Nasonova O.N., Shurkhno E.A., Dzhogan L.Ya., and Aizel G.V. (2019b). Physically Based Modeling of the Long-Term Dynamics of Water Balance and Snow Water Storage Components in the Ob–Irtysh River Basin. Water Resources, 46(4), 493-503, DOI: 10.1134/S0097807819040109.

Hempel S., Frieler K., Warszawski L., Schewe J., and Piontek F. (2013). A trend-preserving bias correction – the ISI-MIP approach. Earth Syst. Dynam., 4(2), 219-236, DOI: 10.5194/esd-4-219-2013, 2013.

Kattsov V.M., Walsh J.E, Chapman W.L., Govorkova V.A., Pavlova T.V., and Zhang X. (2007). Simulation and projection of Arctic freshwater budget components by the IPCC AR4 global climate models. J. Hydrometeorol., 8(3), 571-589, DOI:10.1175/JHM575.1.

Khon V.Ch. and Mokhov I.I. (2012). The hydrological regime of large river basins in northern Eurasia in the XX–XXI centuries. Water Resources, 39(1), 1-10, DOI: 10.1134/S0097807812010058.

Kislov A.V., Grebenets V.I., Evstigneev V.M., Konishchev V.N., Sidorova M.V., Surkova G.V., and Tumel' N.V. (2011). Effects of possible climate warming in the 21st century for Northern Eurasia. Vestnik MGU, Ser. 5, Geography, 3, 3-8 (in Russian with English summary).

Koirala S., Hirabayashi Y., Mahendran R., and Kanae S. (2014). Global assessment of agreement among streamflowprojections using CMIP5 model outputs. Environ. Res. Lett., 9(6), 064017, DOI: 10.1088/1748-9326/9/6/064017.

Krysanova V. and Hattermann F.F. (2017). Intercomparison of climate change impacts in 12 large river basins: overview of methods and summary of results. Climatic Change, 141, 363-379.

Nasonova O.N. (2011). Application of a land surface model for simulating rainfall streamflow hydrograph: 2. Comparison with hydrological models. Water Resources, 38(3), 274-283, DOI: 10.1134/S0097807811030080.

Nasonova O.N., Gusev Ye.M., and Kovalev Ye.E. (2009). Investigating the Ability of a Land Surface Model to Simulate Streamflow with the Accuracy of Hydrological Models: A Case Study Using MOPEX Materials. J. Hydrometeorology, 10(5), 1128-1150, DOI: 10.1175/2009JHM1083.1.

Nasonova O.N., Gusev Ye.M., Kovalev E.E., Ayzel G.V., and Chebanova M.K. (2021). Projected changes in water balance components of 11 large river basins during the 21st century and their uncertainties. Water Resources, 48(5), 666-675, DOI: 10.1134/S0097807821050158.

Nasonova O.N., Gusev Ye.M., Kovalev E.E., Ayzel G.V., and Panysheva K.M. (2019). Projecting changes in Russian northern river runoff due to possible climate change during the 21st century: A case study of the Northern Dvina, Taz and Indigirka rivers. Water Resources, 46(Suppl. 1), S145-S154, DOI: 10.1134/S0097807819070145.

Nasonova O.N., Gusev E.M., Kovalev E.E., and Shurkhno E.A. (2021). Global estimates of changes in the terrestrial water balance components in the context of possible climate changes. Water Resources, 48(4), 459-473, DOI: 10.1134/S0097807821040151.

Nasonova O.N., Gusev Ye.M., Volodin E.M., and Kovalev E.E. (2018). Application of the land surface model SWAP and global climate model INMCM4.0 for projecting runoff of northern Russian rivers. 2. Projections and their uncertainties. Water Resources, 45(Suppl. 2), S85-S92, DOI: 10.1134/S0097807818060271.

Semenov S.M. and Gladilshchikova A.A. (2022). Scenarios of anthropogenic changes in the climate system in the XXI century. Fundamental and Applied Climatology, 8(1), 75-106, DOI: 10.21513/2410-8758-2022-1-75-106.

Shkolnik I.M., Meleshko V.P., Karol I.L., Kiselev A.A., Nadyozhina E.D., Govorkova V.A., and Pavlova T.V. (2014). Expected climate change on the territory of the Russian Federation in the XXI century. Trudy GGO, 575, 65-118 (in Russian).

Weedon G.P., Gomes S., Viterbo P., Shuttleworth W.J., Blyth E., Oesterle H., Adam J.C., Bellouin N., Boucher O., and Best M. (2011). Creation of the WATCH Forcing Data and its uses to assess global and regional reference crop evaporation over land during the twentieth century. J. Hydrometeorol., 12, 823-848, DOI: 10.1175/2011JHM1369.1.