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Estimation of Hydropower Plants Energy Characteristics Change Under the Influence of Climate Factors

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Abstract— **The impact of climate change on operation of the largest Russian hydropower cascade was addressed. A coupled climate-hydropower simulation was fulfilled assuming a model of the cascade taking into account the real dynamics of the hydro-engineering system. An ensemble approach was applied to CMIP5 climate simulation data using the models' discrimination based on a validation procedure. It has been found that the projected climate change will make a noticeable impact both on the annual power generation amount and the guaranteed power generation capacity. The found evidence should be taken into account when developing new rules of water resources use for the hydropower plants reservoirs.**

Keywords: climate change, Angara–Yenisey hydropower plants cascade, CMIP5 climate models, RCP4.5 scenario, capacity, electricity production

I. INTRODUCTION

The climate change was foreseen almost half a century ago and was getting more and more pronounced during the last decades. The world is getting warmer, even if the warming rate is much closer to the moderate climate scenarios rather to dramatic ones. However, the consequences of climate change are already evident around the world both in meteorological records and everyday life.

Russia is one of the areas where climate change is being manifested in the most remarkable way. The rise of the seasonal temperatures across the Russian territory is up to five times stronger as compared to the global average values. This intense increase of the air temperatures unavoidably impacts all the aspects of heat and mass transfer in the climate system including hydrologic processes.

Detection of the hydrologic changes is quite difficult due to a certain deficit of the hydrologic observation data combined with the high natural variability of the precipitation and runoff. Nevertheless, the shift of the hydrologic regimes is getting more and more noticeable in the course of modern climate change. The most obvious effect of the climate change on the runoff in Russia is a change of the inter-annual runoff distribution. Warming winters and earlier springs result in an increase of the winter runoff combined with a decrease of the spring runoff peaks across the country. Growth of the summer precipitation leads to an increase in the summer minimum runoff values. The change of the inter-annual runoff distribution to a more even shape is one of the most obvious hydrologic effects of climate change in Russia. Besides, there is strong evidence of the increasing trend of the annual river runoff in the northern parts of the country caused by climate change.

Observed runoff changes should be seen as an eve of the long-term shift of the runoff regimes which will unavoidably impact all the aspects of water use in the country. Particularly, it means a significant change in the operation conditions for the hydro-power plants (HPP), which are very likely to remain a leading renewable generation technology in Russia for many decades to come. Development of adaptation measures to climate change is needed to ensure efficient operation of the national power systems under the changing climate conditions.

Published research papers are focused much more on the hydrologic changes that are observed or projected for the Russian territory rather than on the water-power nexus under these changing climate conditions [1], [2], [3], [4]. Studies of the climate change impact on the HPP output are rather scarce [5], [6]. Moreover, all of these studies use a linear model to estimate a runoff changes effect on the amount of electricity generation. That is quite a restrictive assumption which completely neglects non-linearity of the real hydro-engineering systems. So, the impact of the climate change on real operation of the Russian HPPs remains heavily under-investigated.

The aim of our work was to propose a methodology to couple climate simulation with detailed modeling of the HPPs operation considering restrictions and conditions which should be satisfied by operation of the real power systems. The Angara-Yenisey hydropower cascade was taken as a modeling area.

In this study we follow the modern approach to the estimate of climate change impact on the hydropower generation [7], [8], [9], using the climate models ensemble results as the input data to the hydro-engineering calculations.

Thus, the paper is organized as follows. First, we describe the methodology of climate projections and hydro-engineering modeling. Further, we examine the climate data used; the assumptions used for the climate simulations and present the climate projections results. Finally, we will introduce the results of a coupled climate-hydropower simulation under a selected climate scenario.

II. METHODOLOGY

A. *Climate simulation*

The most reliable runoff projection methods are based on development of the ensemble estimations using the results of the global or regional climate models when an ensemble approach allows for a certain compensation of the random modelling uncertainties. The ensemble formation strategy is one of the key questions to assure proper skill of the developed ensemble projections [10]. The fact is that each research problem requires selection of a unique model ensemble which is the most appropriate one to represent a climate parameter in question.

The object of our climate study was assessment of the long-term runoff trends in Russia. That is why we have decided to use the model discrimination strategy considering the ability of each model to represent the long-term runoff dynamics across the country. This ability was quantified as a correlation coefficient between the modelled runoff fields and the hydrologic measurements data. A moving average smoothing was used to filter the long-term dynamics. The models were ranked considering the mean and maximum values of their correlation coefficient in the vicinity of each measurement station. The ensemble formed as a result of this procedure was used for further climate calculations. A runoff adjustment coefficient was calculated as a ratio of the future area-average runoff on a given area to a one corresponding to a reference period 2006-2017.

B. *Hydro-power simulation*

Volume of month and decade water flow was calculated using adjustment coefficients which were defined as explained above.

$$Q'_{ij} = Q_{ijl} * k_{ij} \tag{1}$$

Where: Q'_{ij} — average monthly side inflow for 2045-2054;

Q_{ijl} — average monthly side inflow for 1916-2006;

k_{ij} — adjustment coefficient,

i — river section,

j — year in period 1916-2006;

l — month from January to December.

The basic equation of the mathematical model of an HPP cascade (2) is the water-balance equation, which reflects the law of mass conservation, and is written in the form

$$\overline{Q}_{\mathrm{tr}ij} = \overline{Q}_{\mathrm{f}ij} + \overline{Q}_{\mathrm{tri}(j-1)} \pm \overline{Q}_{\mathrm{r}ij} - \overline{Q}_{\mathrm{evap}ij} - \overline{Q}_{\mathrm{dis}ij} - \overline{Q}_{\mathrm{ice}ij} \tag{2}$$

Where: $\overline{Q}_{\mathrm{tr}ij}$ and $\overline{Q}_{\mathrm{tri}(j-1)}$ are the average-interval flow rates of water in the tailrace in the i-th effective interval at the *j*-th and (*j* – 1)-th sites;

$\overline{Q}_{\mathrm{f}ij}$ is the average-interval flow rate of the effective hydrograph;

$\overline{Q}_{\mathrm{r}ij}$ is the average-interval flow rate of water of the reservoir;

$\overline{Q}_{\mathrm{evap}ij}$ is the average-interval loss of water flow due to evaporation from the reservoir;

$\overline{Q}_{\mathrm{dis}ij}$ is the average-interval irrevocable discharges of water from the reservoir in the i-th effective interval at the *j*-th site of the HPP;

$\overline{Q}_{\mathrm{ice}ij}$ is the average monthly losses of water flow from the reservoir due to ice formation.

Generating capacity of HPP is defined according to (3).

$$N_{\text{гэс}\,t} = Q_t \cdot \left(\frac{Z_{\mathrm{UP}}^{\mathrm{B}\,t} + Z_{\mathrm{UP}}^{\mathrm{E}\,t}}{2} - Z_{\mathrm{DP}}(Q_t) - \Delta h \right) \cdot k_N \tag{3}$$

Where $Z_{\mathrm{UP}}^{\mathrm{B}\,t}$ — beginning level of upstream pool, m;

$Z_{\mathrm{UP}}^{\mathrm{E}\,t}$ — ending level of upstream pool, m;

Z_{DP} — average level of downstream pool, m;

Q_t — water flow into downstream pool, m^3/sec;

Δh — loss of water pressure is water flow structures, m;

k_N = 9.81·η_{HPS},

where: η_{HPS} is defined by performance characteristics of HPP.

III. RESULTS AND DISCUSSION

A. *Runoff projections*

The CMIP5 (Coupled Model Intercomparison Project Phase 5) global climate modeling archive was used was calculations. The main reason for our preference towards the global climate models as opposed to the regional ones was a certain deficit of the regional climate simulations data for the East Siberian domain where the considered area is located.

The list of the models used for ensemble formation is presented in Table I. The HPPs measurements data for runoff were used for validation and models discrimination in the whole Russian area. The models selected for ensemble calculations are denoted with an asterix in Table I.

TABLE I. LIST OF CMIP5 MODELS USED FOR THE ENSEMBLE ESTIMATIONS. THE MODELS SELECTED FOR MAKING ENSEMBLE ESTIMATIONS ARE MARKED WITH ASTERIX

Model Name	**Institute**
ACCESS 1.0 ACCESS 1.3	Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology, Australia (CSIRO-BOM) [11]
bcc-csm1-1-m* bcc-csm1-1	Beijing Climate Center, China (BCC) [12]
BNU-ESM	Beijing Normal University, China(BNU) [13]
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada (CCCma) [14]
CCSM4*	National Center for Atmospheric Research (NCAR) [15]
CESM1-BGC*, CESM1-CAM5 CESM1-CAM5.1-FV2* CESM1-FASTCHEM*	Community Earth System Model Contributors (NSF-DOE-NCAR) [16]
CMCC-CESM CMCC-CMS* CMCC-CM	Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy (CMCC) [17]
CNRM-CM5	Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, France (CNRM-CERFACS) [18]
CSIRO-Mk 3.6.0	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia (CSIRO-QCCCE) [19]
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University, (LASG-CESS) China [20]
FIO-ESM*	The First Institute of Oceanography, SOA, China (FIO) [21]
GISS-E2-H GISS-E2-H-CC* GISS-E2-R GISS-E2-R-CC*	NASA Goddard Institute for Space Studies, USA (NASA GISS) [22]
GFDL-CM3 GFDL-ESM2G GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory, USA (NOAA GFDL) [23], [24]
HadCM3 HadGEM2-CC HadGEM2-ES	Met Office Hadley Centre, UK (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais, Spain) [25]
inmcm4	Russian Academy of Sciences, Institute of Numerical Mathematics, Russia (INM) [26]
IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR*	Institut Pierre Simon Laplace, France (IPSL) [27]
MIROC-ESM MIROC-ESM-CHEM MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan (MIROC) [28], [29]
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany (MPI-M) [30]
MPI-ESM-MR	
MRI-CGCM3 MRI-ESM1*	Meteorological Research Institute, Japan(MRI) [31]
NorESM1-M NorESM1-ME	Norwegian Climate Centre (NCC) [32]

TABLE II. POWER GENERATION CAPACITY N AND AVERAGE ANNUAL ELECTRICITY GENERATION E

HPP	**N_{inst}, MW**	**Current characteristics**		**characteristics with climate impact**		**Change, %**	
		$N_{90\%\ jan}$, MW	***E_{av}, mil kWt.h***	***$N_{90\%\ jan}$, MW***	***E_{av}, mil kWt.h***	***$N_{90\%\ jan}$***	***E_{av}***
Irkutskaya	662	340	4 100	340	4 170	0	2
Bratskaya 394 m	4 500	2 030	22 046	2 115	22 408	4	2
Ust-Ilimskaya	3 840	1 856	21 402	1 938	22 021	4	3
Boguchanskaya	2 997	1 506	17 308	1 541	17 905	2	3
Sayano-Shushenskaya	6 400	1 820	23 597	1 820	22 935	0	–3
Mainsksya	321	135	1 597	135	1 577	0	–1
Krasnoyarskaya	6 000	1 800	20 070	1 800	19 800	0	–1
Total	24 720	9 487	110 120	9 689	110 816	2	1

The moderate rcp 4.5 climate scenario[33] was taken for projections making. The projection results are consistent with the seasonal trends being currently observed (Fig. 1). The runoff is increased during the winter almost everywhere in the country which often has a decrease of a spring runoff as a consequence. An increase of summer precipitation on a significant part of Russian territory results in an enhancement recharge.

B. *Results of the coupled climate-hydropower simulations*

Increase in air temperature leads to a change in volume and geographical distribution of precipitation, this change affects areas with high precipitation volume as well as arid areas. Changes in precipitation distribution over territory cause a change in quantitative characteristics of river water flow and consequently change in performance characteristics of hydropower plants (HPP) situated there.

Aim of this research was to estimate the change in energy characteristics of HPPs on certain rivers over a certain period. We considered Angara-Yenisei HPP cascade including Irkuskaya HPP, Bratskaya HPP, Ust-Ilimskaya HPP and Boguchanskaya HPP on Angara river and Sayano-Shushenskaya HPP, Mainsksya HPP and Krasnoyarskaya HPP on Yenisei river. HPP characteristics (mean annual output E_{av} and installed and guaranteed winter generating capacity N_{inst} and $N_{90\%\ jan}$, respectively) are shown in Table II and Fig. 2-4.

In the course of our research we compared energy generation capability using a criterion of average annual electricity generation.

Estimation of climate impact for 2045-2054 period was made based on observed data for water flow in existing river observation points for 1916–2006 adjusting for the expected impact of climate factors on multi-year average of annual and month water flow.

Water inflow into HPPs reservoirs was calculated according to formula (1) considered by the following sections: inflow into the Lake Baikal and Sayano-Shushenskaya HPP water reservoir and side inflow into sections of river between the Angara-Yenisey HPP cascade HPPs Irkuskaya HPP — Bratskaya HPP, Bratskaya HPP – Ust-Ilimskaya HPP, Ust-Ilimskaya HPP – Boguchanskaya HPP on Angara River and Sayano- Shushenskaya HPP – Krasnoyarskaya HPP on the Yenisey River. Side inflow in an interval between Mainsksya HPP and Sayano-Shushenskaya HPP was not considered separately due to its low volume.

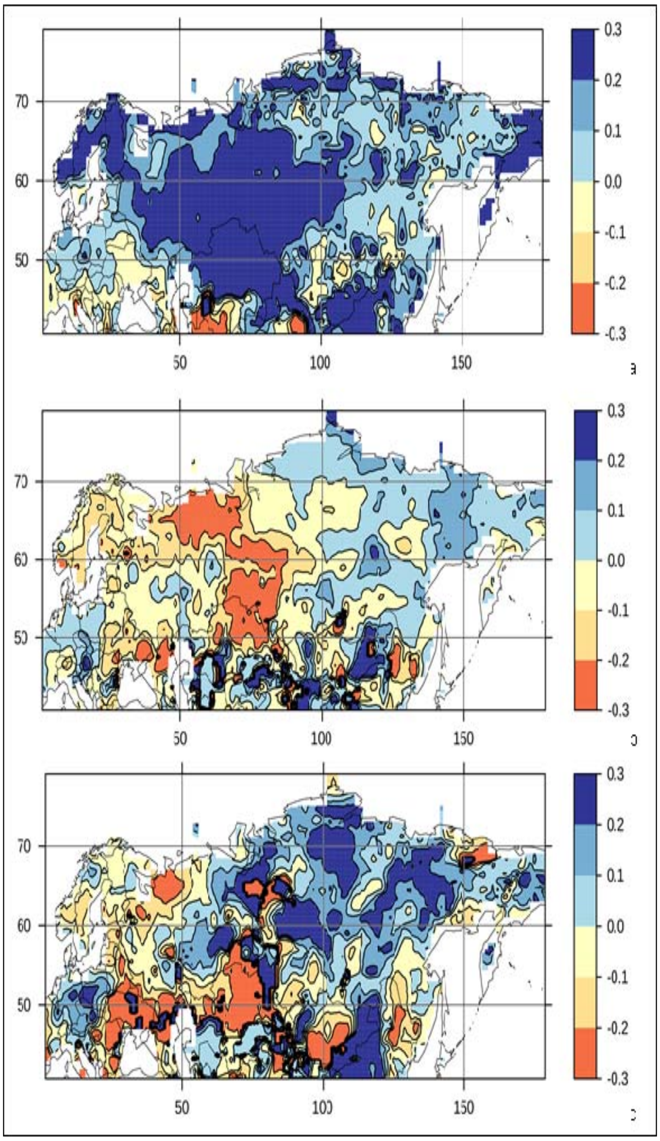

Fig. 1. Relative change of the monthly runoff in 2045-2054 as compared with 2006-2017: a — February, b — May, c — August

Analyses for average annual energy generation and guaranteed winter power generation capacity according to equations (2)-(4) were performed using “Cascade” software package [34].

Requirements of water resources users to water management were assumed at a current level. No limitations on HPP power generation from energy network were included in analyses. Existing rules of water resources use were taken as HPP water reservoir water management rules [35], [36], [37], and [38].

Results of our analysis are shown in Table II and Fig 2-4.

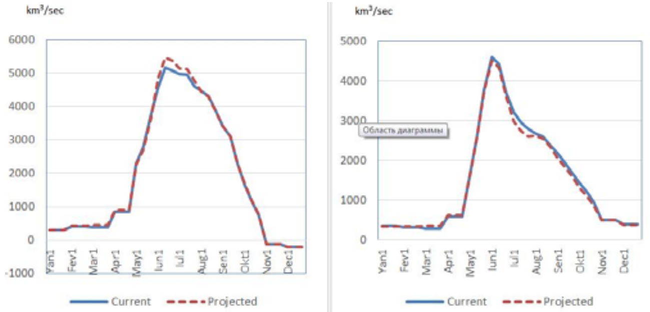

Fig. 2. Current and projected distribution of month inflow into Irkutskaya HPP (a) and Sayano-Shushenskaya HPP water reservoir (b)

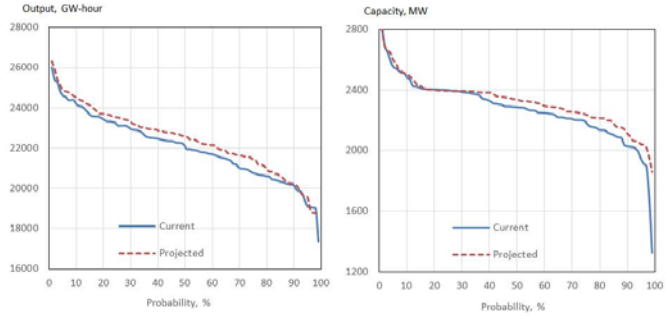

Fig. 3. Current and projected distribution of annual output (a) and average guaranteed winter generating capacity of Bratskaya HPP (b)

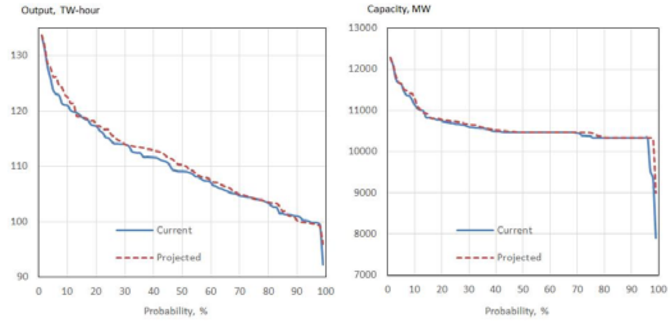

Fig. 4. Current and projected distribution of annual output (a) and average guaranteed winter generating capacity of Angara-Yenisei HPP cascade (b)

Above results demonstrate that climate factors make a certain impact of energy characteristics of existing HPPs, the impact is made on both average annual power generation volume and guaranteed winter power generation capacity. Revealed increase in power characteristics of HPP (annual output and average guaranteed winter generating capacity) is not directly proportional to the increase in water inflow. Such feature is caused by seasonal fluctuation of inflow and oscillation of water pressure at HPP due to seasonal management of outflow in HPP water reservoirs. This impact will need to be taken into account when designing future rules for the HPPs reservoirs.

IV. CONCLUSIONS

- The climate change in Russia will result in statistically significant changes in the runoff regimes in many parts of the country to the mid-twenty-first century even for the moderate climate scenario.
- Revealed seasonal character of climate factors impact on intra-annual distribution of water flow leads to an increase in low water season water flow and a decrease in high water season water flow.
- Performed analysis of climate factors impact of energy characteristics of the Angara-Yenisey HPP cascade had shown a certain increase in average annual energy generation volume.
- Disproportional increase in power characteristics of HPP (annual output and average guaranteed winter generating capacity) comparing to increase in water inflow is revealed.

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