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Selection of an Ensemble of Atmospheric and Oceanic General Circulation Models of the CMIP-6 Project for estimating possible runoff changes in the Volga and Kama basins.

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Abstract In modern conditions of climate change and increasing pressure on water resources, river forecasting is becoming one of the urgent tasks of rational water use. The main tool for long-term climate characteristics prediction are the Atmospheric and Oceanic General Circulation Models (AOGCM). In this paper, we assessed the quality of a number of climatic characteristics by the CMIP-6 (Coupled Model Intercomparison Project, Phase 6) AOGCMs for the Volga and Kama basins in order to access the possibility of their use to river runoff in the 21st century forecasting. A comparison was made of the data produced by the models for the period 1985-2014 and ERA5 reanalysis data (temperature and precipitation) as well as with observational data on river runoff. The reproduction error of the average values, standard deviations, and the coincidence of series trends evaluated. It is shown that the models demonstrate very different quality of the reproduction of water balance characteristics results. When using these models to predict possible changes in river flow in the future, it is necessary to take into account these uncertainties and apply methods to reduce the impact of systematic errors.

1 Introduction.

There have been significant changes in the water regime under the influence of climate change in many regions of Russia, as shown by numerous studies of the consequences of modern climate change and their impact on river flow, as well as the analysis of long-term series of annual flow [1, 3, 11 and many others]. With a high probability this trend will continue in the coming decades, so the problem of assessing changes in river runoff becomes highly relevant. Water management and hydraulic engineering design also requires a reliable determination of the future river flow regime parameters. Assessing the possibility of using global climate modelling data to predict river runoff changes in the Upper Volga and Kama basins is the purpose of this paper.

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The Intergovernmental Panel on Climate Change is responsible for assessing observed and expected climate changes and their impacts. The results of this work are formalized mainly in the form of IPCC Assessment Reports. To date, 6 evaluation reports have been prepared. The sixth was released in 2021-22, which is based on scenario calculations using modern models created as part of the international project CMIP6 (CoupledModelIntercomparisonProject, Phase 6: Project for intercomparison of coupled models (atmosphere and ocean) sixth phase) [7].

The data of the new generation global atmospheric and ocean general circulation models (AOGCMs) are actively used to assess future climate changes and river flow characteristics at the present time. AOGCMs give out almost all fields of the atmosphere, ocean, cryosphere and the active layer of the land. At the same time, the attitude of specialists to runoff forecasts based on AOGCM data is often sceptical. It is believed that AOGCMs contain simplified schemes for calculating river runoff, which do not allow adequate reproduction of runoff fluctuations. But, one cannot ignore the fact that the leading scientific centres (specialists) of world hydrometeorology are constantly improving the developed models [6]. However, an obligatory step before working with the data of global models is their preliminary testing in terms of the quality of reproduction of the characteristics of the modern climate [2, 3, 6, 8,12,13].

Models of the CMIP6 project have not yet been tested in the territories of the Volga and Kama basins, so this work is interesting and relevant.

2 Materials and methods.

In this work, testing was performed in relation to the reproducibility for the sums of annual precipitation, the annual sums of positive monthly temperatures and the river flow. These parameters were chosen for the following reasons: First, precipitation is the main input characteristic of the terrestrial water balance, as well as the most carefully developed and tested characteristic of AOGCMs; the sums of positive temperatures are an important agrometeorological indicator, as well as a factor in changing evapotranspiration and direct river runoff, and they are usually well reproduced by AOGCMs due to the smoothness of the characteristic fields. Stock is a characteristic that is not as well represented in the models. Usually, the runoff is used to correct the closure of the water balance. When analysing the information on river flow provided within the framework of the CMIP6 project, it was found that out of more than 50 models participating in the project, only 37 provide data on flow in a full volume for research. For comparison: at the previous stage of the CMIP5 project, 29 out of 50 models provided information on runoff, and in the CMIP3 project, no more than 10 models (https://data.ceda.ac.uk/badc/cmip6/data).

The outputs of climate models include two variables that characterise river runoff: total runoff (total runoff flux, mrro) and surface runoff (surface runoff flux, mrros). When analysing the data, it was found that the data on the mrros variable (surface runoff) are significantly underestimated, which is consistent with the data given in [6]. Therefore, the reproduction of the variable mrro (total runoff), which includes the underground component, is investigated in the work. However, for studies of long-term (climatic) runoff, this variable is suitable as a long-term component of the water balance of the territory.

As a characteristic of the current climate in the presented work, the data of the ERA5 global re-analysis prepared by the ECMWF (European Center for Medium-Range Weather Forecasts) for 1985-2014 were used.

The ERA5 reanalysis was developed by the European Center for Medium-Range Forecasts and is the fifth generation of the ECMWF global atmospheric observation reanalysis. Its main advantages over other reanalyses are its continuing series of global hourly, daily and monthly average data from 1950 to the present, as well as its high spatial

(0.25° x 0.25° in longitude and latitude) and temporal (1 h) data resolution with atmospheric parameters at 37 pressure levels represents significant progress in the 10 years achieved in modelling and data assimilation since the release of ERA-Interim [4]. The quality of the reanalysis data was considered for the European territory of Russia in [5] and it is shown that precipitation has a noticeable systematic error only for the forest-tundra zone and the semi-desert zone, and the systematic error of temperature interpolation for more than 50% of the points according to weather stations and ERA -5 does not exceed 0.4°C, and its median value is close to 0°C.

Reanalysis is, in fact, dynamically smoothed and consistent data of a certain set of archival observations, using a hydrodynamic model with a fixed configuration. Therefore, these data were used to determine the reproduction of precipitation and temperatures, that is, the model data were compared with the reanalysis data.

At present, new-generation global atmospheric and ocean general circulation models (AOGCMs) are actively used to assess future climate changes and river runoff characteristics. At the same time, AOGCM data does not always have sufficient accuracy. As a result, it is customary to use an ensemble of models to increase the reliability and stability of the results. Most researchers follow the path of preliminary selection of models, based on a comparison of the observed and model climate for any region [2, 3,12,13 and many others]. The data of the ERA5 global re-analysis prepared by the ECMWF (European Center for Medium-Range Weather Forecasts) for 1985-2014 as a characteristic of the current climate were used.

The quality of 45 models of the CMIP-6 project (Table 1) was assessed in terms of optimal reproduction of climatic characteristics in the Volga and Kama basins for the 30-year period 1985-2014 (2014 ends the "historical" period of the AOGCM of the release of CMIP6).

For each model, the reproduction error of the average values, standard deviations, and the area of coincidence of precipitation trends for the period 1985-2014 was calculated.

Table 1. List of the general circulation models of the atmosphere and ocean of the CMIP-6 Project considered in this work.

MPI-ESM1-2-HR	UKESM1-0-LL	INM-CM5-0
MPI-ESM1-2-LR	GFDL-CM4	IPSL-CM5A2-INCA
MRI-ESM2-0	GFDL-ESM4	IPSL-CM6A-LR-INCA
GISS-E2-1-G	NESM3	KIOST
GISS-E2-1-G-CC	SAM0-UNICON	MIROC6
GISS-E2-1-H	CIESM	MIROC-ES2L
GISS-E2-2-H	MCM-UA-1-0	HadGEM3-GC31-LL
CESM2	ARCCSS	HadGEM3-GC31-MM
CESM2-FV2	E3SM-1-0	UKESM1-0-LL
CESM2-WACCM	E3SM-1-1	UKESM1-1-LL
CESM2-WACCM-FV2	E3SM-1-1-ECA	BCC-CSM2-MR
NorCPM1	EC-Earth-Consortium	BCC-ESM1
NorESM2-LM	FIO-ESM-2-0	CAMS-CSM1-0
NorESM2-MM	MPI-ESM-1-2-HAM	CAS-ESM2-0
KACE-1-0-G	INM-CM4-8	FGOALS-f3-L

3 Results and discussion.

Practically all models used overestimate the value of the annual precipitation in comparison with the observed one. For this characteristic, the error of the modulo mean varies from 6% to 63%, with an average error of 32%. The average standard deviation error for the study area for 45 models is 40%. The coincidence of the direction of trend of the model values with the observed ones was checked for each grid point. The trend of annual precipitation on average for all models is reproduced unsatisfactorily - the area with a coinciding trend is 31% for all 45 models

If we consider as a threshold criterion an error of less than 30% in the mean and less than 35% in the standard deviation, then 9 models FGOALS-f3-L, GISS-E2-2-H, CESM2, BCC-CSM2-MR, E3SM- 1-1-ECA, BCC-ESM1, NorESM2-MM, CESM2-WACCM, FIO-ESM-2-0. In our country, most researchers use an ensemble of models to increase the stability of the results [9-13 and many others]. The use of the ensemble makes it possible to smooth out the individual errors of the models; the result obtained from the ensemble demonstrates the minimum possible errors when using the AOGCM data.

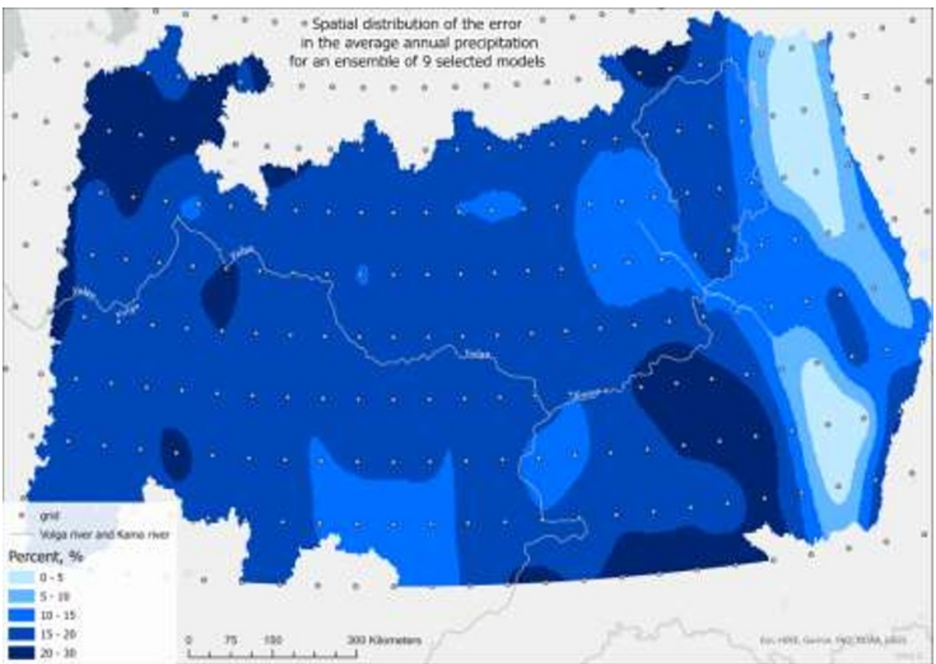

Fig. 1. Spatial distribution of annual precipitation reproducing error for an ensemble of 9 models

The average error in reproducing the annual precipitation totals for an ensemble of 9 models is 19.9% (Fig. 1), their standard deviation is 27.3%, and the share of the trend sign coinciding with the area is 45.6%.

The temperature fields are reproduced much better due to their features - this is a smoother field with gradual changes, so the temperature characteristics are not limited when choosing an ensemble. For example, for an ensemble of 9 models selected for the best reproduction of annual precipitation sums, the errors in reproducing the sums of positive temperatures are as follows. The average reproduction error in annual sums of positive temperatures over space for the selected ensemble is 11.9%, which is 1.7 times less than the average error for the ensemble for the annual precipitation. The average standard deviation error for this indicator is 20.7%, it’s also lower than the annual precipitation error. For all 9 models of the ensemble selected according to annual precipitation, the share of the trend sign coincidence with the area for the criterion of the sums of positive temperatures is 100%, which is natural, since it reflects the dynamics of temperature changes in response to the dynamics of greenhouse gas emissions incorporated in the CMIP6 scenarios.

The reproduction of the river runoff layer (mm) was assessed by comparison with the annual runoff data from cartographic data [1], since this data presents a spatial generalization of data from direct observations of runoff for the period 1985-2014. Runoff data without errors (negative or unrealistic values) are presented in the SMIP-6 project only in 26 AOGCMs. The average spatial annual runoff reproduction error for an ensemble of 9 selected models is 25% and varies from 19% (CESM2) to 38% (FGOALS-f3-L). If we take the average error threshold of 21% as a criterion, then the best 5 models are EC-Earth3, EC-Earth3-CC, UKESM1-0-LL, MRI-ESM2-0, CESM2-WACCM.

The average spatial error in the reproduction of annual runoff indicators for an ensemble of 5 selected models is 22%. The spatial distribution of the averaged error over an ensemble of 26 models is shown in Fig. 2a, for an ensemble of 5 models - Fig.2.b. It is easy to see that the error naturally increases to the south, in the zone of low runoff. This is quite natural, since the smaller the value, the larger the relative error. Nevertheless, the choice of the most qualitative models can significantly reduce the estimation error.

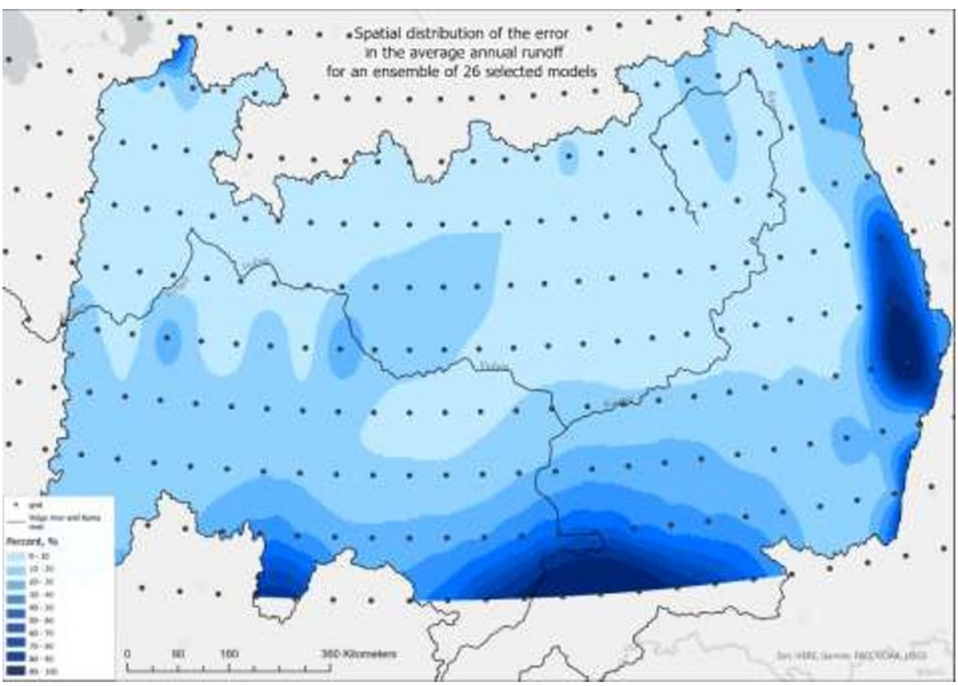

Fig. 2.a Spatial distribution of the error in reproducing the mean value of annual precipitation for an ensemble of 26 models

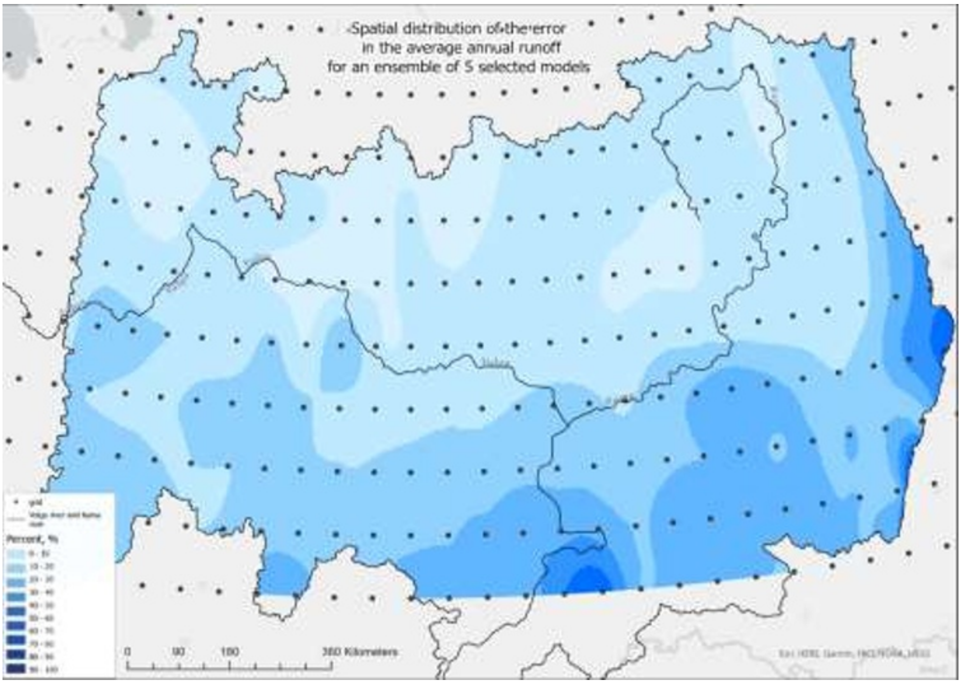

Fig. 2.b Spatial distribution of the error in reproducing the mean value of annual precipitation for an ensemble of 5 models

As you can easily see, only one model CESM2-WACCM is in the category of the models best both in terms of precipitation and runoff - so there is no guarantee that a model that reproduces one characteristic well will reproduce the others the same well. As shown earlier [13], there is the same problem with estimating the statistical parameters of the series - the mean value and variance of the model data. The models show very different quality results of reproducing these characteristics. When using models to calculate possible changes in river flow in the future, these uncertainties should be taken into account and methods should be applied to reduce the effect of systematic errors, such as the use of data on relative changes in characteristics. It is desirable to make estimates of future runoff not only based on AOGCM data, but also using various hydrological models, the input data for which will be AOGCM data on precipitation, temperatures, etc. [8].

4 Conclusions.

Thus, different models of general atmosphere and ocean circulation show very different quality of reproduction of water balance characteristics results. Only one model among investigated ones, CESM2-WACCM is in the category of models with the best results for both precipitation and runoff. The quality of reproduction of different characteristics can vary greatly with the same model. When using these models to predict possible future changes in streamflow, these uncertainties must be taken into account and methods must be used to reduce the effects of systematic errors. It is desirable to make estimates of future streamflow not only from AOGCM data, but also from various hydrologic models.

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