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РЕЧНОЙ СТОК ВОЛГИ В ТЕПЛЫЕ КЛИМАТИЧЕСКИЕ ЭПОХИ ГЕОЛОГИЧЕСКОГО ПРОШЛОГО, В ПЕРИОД ИНСТРУМЕНТАЛЬНЫХ НАБЛЮДЕНИЙ И СЦЕНАРНОГО БУДУЩЕГО

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Анализируются особенности изменения стока Волги в микулинское межледниковье (~125 тыс. лет назад), оптимуме голоцена, в период современного (начиная с 1981 г.) и сценарного (2006–2039 гг.) глобального потепления. Использованы палеоклиматические реконструкции, основанные на данных спорово-пыльцевого анализа ископаемых растений и результатах расчетов, выполненных на ансамбле глобальных климатических моделей программы PMIP-II, а также сценариях потепления климата, осуществленных на ансамбле глобальных климатических моделей программы CMIP3. Гидрологические изменения были оценены на основе модели месячного водного баланса. Наиболее заметные гидроклиматические изменения произошли в микулинское межледниковье, когда годовой речной сток оценивается на 25% меньше его современного значения. Сценарная температура воздуха в бассейне Волги в первую треть текущего столетия была близка к температуре голоценового оптимума, реконструированного на основе палинологических данных. В то же время смоделированный годовой сток был ниже современного. При прогнозируемых и голоценовых климатических условиях, реконструированных в рамках PMIP-II, он оказывается выше современных. Наиболее заметные различия в стоке Волги в теплом климате оптимума голоцена, современном и сценарном периодах проявляются в изменениях внутригодового распределения стока.

Ключевые слова: микулинское межледниковье, оптимум голоцена, современное глобальное потепление, Волга

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1. INTRODUCTION

More than 40 years ago, it was proposed to use past geological epochs as analogues of the future states of natural systems, primarily climate (Budyko et al., 1986). Since then, this direction) of research has developed rapidly, and, in the last twenty years, along with traditional methods of climate reconstruction, climate models have been increasingly used (Joussaume et al., 1999; Kislov, 2001). For many years, an international program has been implemented to compare the results of model climate paleoreconstruction (Paleoclimate Modeling Intercomparison Project-PIMP) as a part of international program of studying past global changes (Past Global Changes – PAGES) (Joussaume et al., 1999). At the same time, the traditional methods of paleoclimate reconstruction (Atlas..., 1992; Paleoclimates..., 2009) are still widely used at both global and regional levels. In our opinion, the parallel development of these directions of research and the comparison of their results is a key condition for the further development of methods for reconstruction of the past climate.

For more than thirty years, the results of paleoclimatic reconstructions have been used to evaluate the river runoff of the past geological epochs at the global, continental, and regional levels (Velichko et al., 1988; Georgiadi, 1990; Atlas..., 1992; Georgiadi, 1992; Velichko et al., 1992; Shiklomanov, 2002; Georgievskii, 2005; Georgiadi et al., 2006; 2007; Paleoclimates..., 2009 et al.). A number of methods have been developed for hydrological reconstructions, starting from relatively simple zonal dependences of annual runoff and climate elements (Velichko et al., 1988; Atlas..., 1992; Georgiadi, 1992; Velichko et al., 1992; Paleoclimates..., 2009), to more complicated water balance models with decadal (Shiklomanov, 2002; Georgievskii, 2005) and monthly resolution (Georgiadi et al., 2006; 2007), and further to atmospheric general circulation models, in which long-term mean river runoff was calculated as the difference between simu-

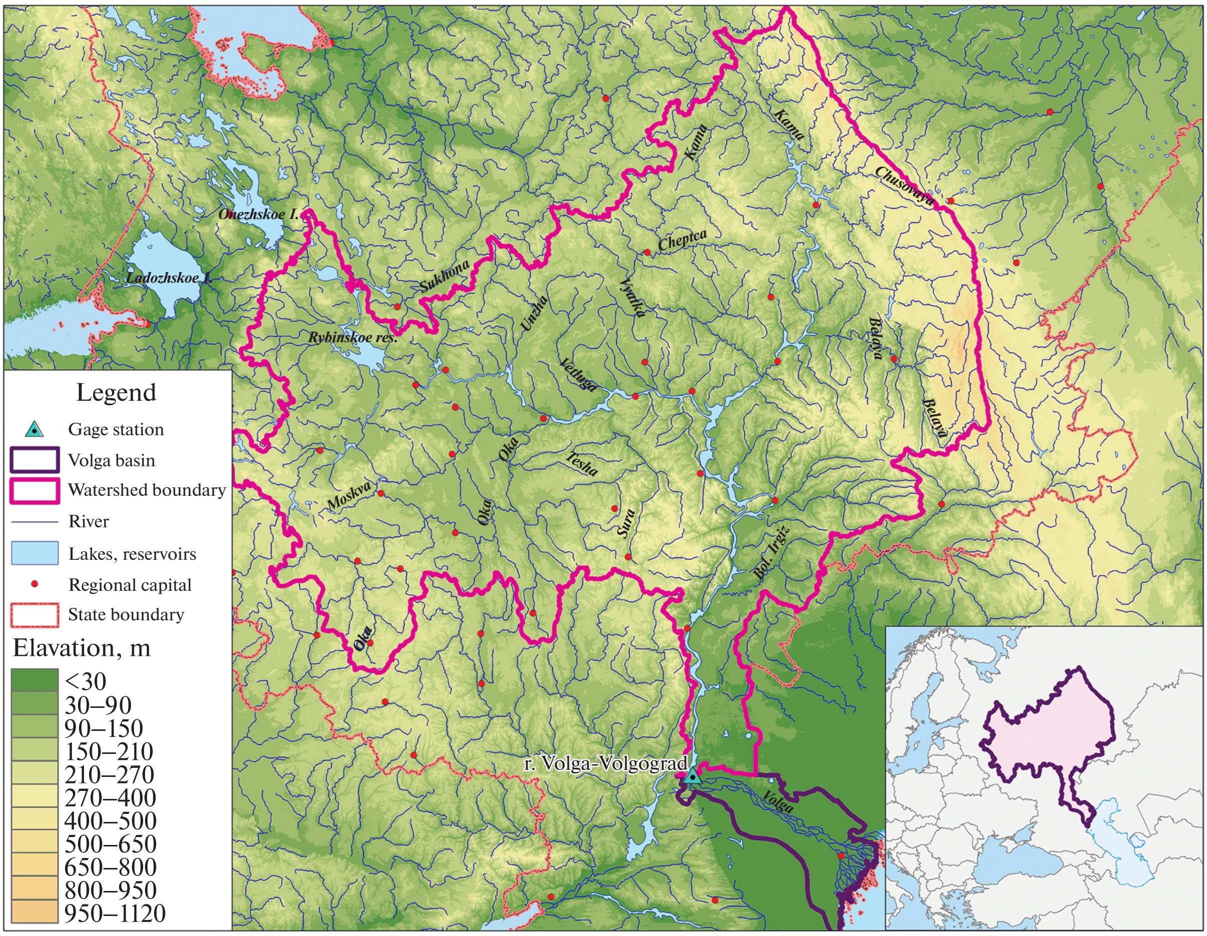

Fig. 1. Location of the Volga River Basin.
Рис. 1. Расположение бассейна реки Волги.

lated atmospheric precipitation and evaporation (Georgiadi et al., 2014).

The article considers the results of estimation of Volga river flow at Volgograd (drainage area of 1360 thous. km^2) under the conditions in last (Mikulino/Eemian) interglacial climatic optimum (~125 ka BP), Late Atlantic optimum of Holocene (6–5.5 ka BP), modern (starting from 1981), and scenario (2006–2039) global warming (fig. 1).

2. METHODS AND MATERIALS

2.1. Monthly Water Balance Model of the Institute of Geography, Russian Academy of Sciences. To evaluate the anomalies of the mean annual runoff and other water balance components within large river basins under the conditions of the geological past and scenario future, the authors have developed and used a model describing the formation of monthly water balance of plain watershed. Water balance calculations are made in cells of a regular grid 1° × 1° along latitude and longitude, covering the river drainage basin. Each cell embraces the layer of soil-ground containing groundwater horizon with active water exchange, typical to the medium-size river drainage basins. The major water balance components are calculated for each such cell, including the flow that forms on the surface and in the under-surface layer and the flow from the underground zone of active water exchange. The obtained values are used to evaluate the total flow out the cell. The obtained annual and seasonal flow in the Volga outlet is calculated using its values evaluated for all cells covering Volga basin down to Volgograd. The input mean monthly values of air temperature and precipitation are specified for each cell. The calculations are made for quasidays (Willmott et al., 1985; Georgiadi et al., 2002; 2014), i.e., the mean monthly values of air temperature and precipitation are interpolated for days within each month with the use of algorithms presented in (Georgiadi et al., 2014).

The model includes fifteen parameters. These parameters were used to calculate the potential evaporation and evaporation, snowmelt, water infiltration into the soil, its filtration into the groundwater horizons, runoff from them, the movement of the soil freezing boundary and the recalculation of the average monthly air temperature into daily one. The parameters were optimized with the use of 50% of cells of observed modern gridded data on potential evaporation and evaporation, mean annual runoff, snow-melt flood runoff, and dry-season runoff uniformly distributed over the Volga basin. The rest set of cells were used to verify the monthly water balance model. Nash–Sutcliffe (Nash et al., 1970) criterion was used as the measure of quality in the estimation of model reliability. The calculated values of this criterion for the annual runoff, as well as for the runoff of snow-melt flood and low-flow season were in excess of 0.75, thus suggesting the satisfactory reliability of the results obtained with the use of the model of monthly water balance.

2.2. Method for Assessing Climate-Induced Changes in River Flow in Instrumental Observation Period. The estimates of the effect of modern global warming (which was assumed to begin in 1981) on the annual and seasonal runoff of the Volga were based on the comparison of its values averaged over 1981–2014 with the appropriate runoff characteristics for the previous period (1931–1980) with relatively cold climate. The calculations used long-term series of the annual and seasonal runoff with eliminated anthropogenic effect (Georgiadi et al., 2014).

2.3. Data

2.3.1. Data of Paleoclimatic Reconstructions. The analysis was based on data on deviations of air temperature and precipitation from their modern values for the last interglacial, reconstructed using paleofloristic data by V.P. Grichuk's method (Paleoclimates..., 2009), and those for Holocene optimum, using the information-statistical method developed by V.A. Klimanov (Paleoclimates..., 2009). The data were interpolated into nodes of a regular grid $1° \times 1°$ along latitude and longitude.

Hydrological estimates for Holocene Optimum were obtained for two variants of paleoclimate reconstructions. In one of them, a statistical error was added to the deviation of climatic characteristic calculated by palinological data (the obtained value was taken as the maximal deviation from the modern values of the climate characteristic). In another case, the statistical error was subtracted from the initial deviation and the obtained value was taken as the minimal deviation.

Data on deviations in January were extended to the months of the cold season (October–March), and July deviations were extended to the months of the warm half year.

Model paleoclimatic reconstructions of the mean monthly anomalies of the climatic characteristics, mentioned above, for the Holocene Optimum were obtained for each month of a long-term mean year by averaging the results of reconstructions made on 18 global climate models included in PMIP-II programme (Joussaume et al., 1999).

2.3.2. Data on Scenario-Based Model Estimates of Climate Changes in the First One-Third of the XXI Century. Since the 1990s, the hydrological conditions of the future climate were often evaluated with the use of scenario-based estimates of global climate changes based on calculations using general atmospheric and oceanic general circulation models (IPCC..., 2007; Georgiadi et al., 2014). According to the definition given by the Intergovernmental Panel on Climate Change (IPCC), the climate scenario is understood to be a plausible (or likely) climate evolution in the future, which is in agreement with the scenarios of emission of greenhouse gases and other atmospheric components. Accordingly, the scenario of climate change implies the difference between climate scenario and the current state of the climate. Scenarios of the CMIP3-Coupled Model Intercomparison Project 3 (Meehl et al., 2007) were used.

The climate scenarios were taken to be scenario groups with the most rapid (A2) and slowest (B1) growth rate of the mean global mean annual air temperature.

Estimates of the climate changes were based on data on model values of the modern (averaged over the period of 1960–1990) and scenario (averaged over periods 2010–2039, which are conventionally referred to 2025) mean monthly air temperature and precipitation and differences between them. The calculations by the results of CMIP3 project were based on an ensemble of 10 models (out of more than 20 models, included in this project). They were selected by A.V. Kislov et al. (2008) by the comparison of the modern simulated and observed climate for The East European Plain. The ensemble-averaged scenarios of variations of mean monthly air temperature and precipitation for each group of the chosen contrast scenarios were obtained by averaging data, contained in each climate model in the specified scenario groups.

2.3.3. Data on the modern observed values of air temperature, atmospheric precipitation, river runoff, and hydrophysical characteristics of soils. The input data for the characteristic of the modern conditions were the following data from weather and hydrometric stations, which were used to prepare the appropriate GIS-layers. The source data were taken from the regional archive of long-term data on the mean monthly values of these elements of meteorological regime (Daily..., 2005), which includes data on air temperature and precipitation over more than 2000 weather stations of the former USSR. In our calculations, we used data on the mean monthly air temperature and mean monthly atmospheric precipitation, which were averaged for each station over time periods exceeding 40–50 years and, in most cases, referred to the period between 1930–1940 and 1980.

GIS-layers of the normal annual mean monthly values were prepared with the use of appropriate data on the mean monthly river runoff over 40 medium-size rivers within the Volga basin taken from the appropriate volumes of the annual publications of The Surface Water Resources of the former USSR. The calculation of the average long-term runoff values was based on long-term records, mostly covering 40–50-year periods (from 1930–1940 to 1980).

For Volga river catchment, data of global GIS, including layers of data on the physical properties of the soils (Tempel et al., 1996), were used to obtain digital fields with a step 1° × 1° along the latitude and longitude for soil water reserves corresponding to the wilting point and field moisture capacity, as well as the specific soil density.

3. RESULTS AND DISCUSSION

3.1. Estimates of Climatic and Hydrological Changes in Warm Geological and Scenario Epochs

3.1.1. Changes of air temperature and atmospheric precipitation. By the scale of changes of the mean long-term averaged annual air temperature, averaged over the Volga basin, the periods under consideration can be arranged in the following order (fig. 2). According to the ensemble-averaged estimates obtained under PMIP-II program, Holocene optimum was warmer than the modern period (for which the basin-averaged temperature, equal to 4°C, was calculated using data from (Daily..., 2005)) by 0.4°C, while if we use the information-statistical method, the positive anomaly will increase to 1.7–2.3°C (Paleoclimates..., 2009). Here and below, anomalies for the minimal and maximal variants of paleoclimatic reconstructions are given (Paleoclimates..., 2009). The latter estimates according to ensemble-averaged calculations carried out under the IPCC program CMIP3 (IPCC..., 2007), are very close to the level of air temperature rise, which is likely under scenario conditions in the first third (2006–2039) of the current century (1.4–2°C). Here and below, the first value refers to scenario family A2 (the most intense average global warming), and the second value, to scenario family B1 (moderate average global warming). The changes were strongest in the warm epoch of the last interglacial (climatic optimum ~125 ka BP), when the deviations reached 4.7°C (Paleoclimates..., 2009).

Changes in the basin-averaged total annual atmospheric precipitation in the Volga basin (the present-day total precipitation, equal to 590 mm, was calculated using data in (Daily..., 2005)), are less pronounced (fig. 2). Thus, according to the results of reconstruction based on the information-statistical method (Paleoclimates..., 2009), the deviation of the total annual precipitation from the modern values for Holocene climatic optimum varied from –3 mm to 17 mm (Paleoclimates..., 2009), and according to PMIP-II, it was 3 mm. The increase in precipitation was maximal in the last interglacial period (76 mm). Under scenario future warming in the first one-third of the current century, the precipitation can increase by 32–24 mm.

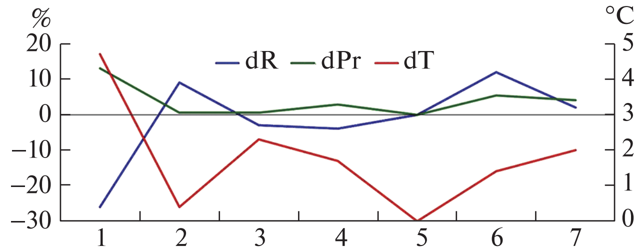

Fig. 2. Deviations of the long-term mean annual hydroclimatic characteristics of river flow dR (%), precipitation dPr (%) and air temperature dT (°C) from their modern values for warm epochs of the past and future for the Volga Basin.

Abscissa: 1 – last interglacial climatic optimum; 2 – Holocene climatic optimum by PMIP-II; 3 – Holocene climatic optimum by (Paleoclimates..., 2009) at maximal deviations of Pr and T; 4 – Holocene optimum by (Paleoclimates..., 2009) at minimal deviations of Pr and T; 5 – present-day value taken as the reference level; 6 – by scenario A2 for 2010–2039; 7 – by scenario B1 for 2010–2039.

Рис. 2. Отклонения средних многолетних средних годовых гидроклиматических характеристик (речного стока – dR (мм), атмосферных осадков – dPr (мм) и температуры воздуха – dT (°C) от современных их значений для теплых эпох прошлого и будущего для бассейна Волги.

На оси абсцисс: 1 – Микулинское межледниковье; 2 – оптимум голоцена по PMIP-II; 3 – оптимум голоцена (по Paleoclimates..., 2009) при максимальных отклонениях Pr и T; 4 – оптимум голоцена (по Paleoclimates..., 2009) при минимальных отклонениях Pr и T; 5 – современный уровень, принятый за ноль отсчета; 6 – по сценарию A2 для 2025 г.; 7 – по сценарию B1 для 2025 г.

3.1.2. River Runoff Changes. The estimate of the anomaly of the Volga *annual runoff* (relative to the average long-term runoff characteristics calculated for the period of 1931–1980 and accepted now as a norm) during Holocene Climate Optimum, based on model ensemble-averaged paleoclimatic reconstruction PMIP-II, amounts to 9% of its current value (fig. 2). On the other hand, calculations of changes in runoff based on paleoclimatic reconstructions using palynological method (Paleoclimates..., 2009) show that the runoff in that period could be 3–4% less than its modern value. In the first third of the current century, the annual the Volga runoff is likely to increase by 12 (scenario A2) and 2% (scenario B1). While under the conditions of the last interglacial, conventional paleoreconstructions (Paleoclimates..., 2009) and calculations show that the Volga runoff was 14% less than its current value.

In the epoch of the last interglacial, the *annual structure of the Volga flow* radically differed from its present-day structure. This is primarily due to the much warmer (by more than 8°C) winter months and the decrease in the length of the period with air temperature below zero from five to three months. The result was that the snow-melt flood wave shifts to earlier dates, its height decreases at a general decrease of the snow-melt flood volume by 36%, the winter runoff increases more than twice, and summer–autumn runoff also somewhat increases.

Under scenario conditions of the first third of the current century (scenarios A2 and B1), the increase of the 1 olga flow in the main seasons of the year is likely to be much less: by 17% (scenario A2) and 4% (scenario B1) during snow-melt flood; in winter, by 6 and 15%; and in summer–autumn, by 19 and 12%. In this case, the snow-melt flood can begin a month earlier without considerable changes in its shape. Basing on the paleoclimatic reconstructions using the palynological method, the snow-melt flood runoff in the period of Holocene Climate Optimum could be 3–4% below its current level, while in winter and summer–autumn period, it was above this level by 19–30 and 8–6%, respectively. Judging from model reconstructions of paleoclimate (PMIP-II), the snow-melt flood flow could be 23% higher than its current values, while in other seasons of the year, it was almost the same as it is now.

3.2. Volga Runoff Changes under Current Global Warming. In the period of modern global warming (starting from 1981), the naturalized annual runoff of the Volga with excluded anthropogenic changes increased by about 8% relative to the preceding period with colder climate (since the 1930s to the 1980), as it was the case in the Holocene climatic optimum (if we proceed from paleoclimatic reconstructions obtained under PMIP-II program) and the scenario future. On the other hand, under the climatic conditions of the Holocene climatic optimum and last interglacial, recovered by conventional methods of paleoclimatic reconstructions, the annual runoff of the Volga, according to our calculations was less than its modern value. The snow-melt flood runoff practically has not changed in the period of modern warming (it increased by 1.5%), while the runoff of the winter low-water season increased most significantly (by 45%), as is also typical of the considered warm epochs of the past, during which the extent of changes of air temperature and atmospheric precipitation could be quite different. Thus, the mean annual air temperature in the period of modern global warming was 1°C higher than the temperature of the base period (which is far below (except for PMIP-II reconstruction) than the considered past and future warm epochs), and the total annual atmospheric precipitation in this period was 25 mm higher than that in the base period (which is comparable with its scenario changes).

4. CONCLUSIONS

1. The most notable hydroclimatical changes in the Volga Basin took place in the warm epoch of the interglacial climatic optimum (125 ka BP), when the basin-averaged annual air temperature was 4.7°C higher than its present-day value, the annual sum of atmospheric precipitation was higher by 76 mm, and the annual river runoff (according to calculations by a model of monthly water balance), was 25% less than its modern value.

2. The climatic conditions of the Holocene climatic optimum (6–5.5 ka BP), reconstructed by palynological data (Paleoclimates..., 2009), are the closest to the scenario thermal regime in the Volga Basin typical in the first third of the current century. Under such conditions, the annual Volga river runoff, calculated by the model of monthly water balance, was less than its modern value. This result is in agreement with estimates of paleorunoff for the Holocene climatic optimum, derived for the Volga from zonal dependences of the annual runoff (Velichko et al., 1988; 1992) and the results of runoff reconstruction by paleomeanders (Sidorchuk et al., 2012). At the same time, under ensemble-averaged scenario climate conditions, obtained under CMIP3 Program for the first third of the XXI century, and paleoclimatic reconstructions for Holocene optimum, based on the ensemble of climate models of PMIP-II Program, the annual river runoff was higher than its current value.

3. In the period of modern global warming (starting from 1981), the naturalized Volga annual runoff (with excluded anthropogenic changes) increased compared with the previous period with colder climate (1931–1980), as well as under the conditions of the Holocene climatic optimum (according to calculations by the model of monthly water balance and paleoclimatic data obtained under PIMP-II program) and scenario future in the first third of the current century. In this case, the snow-melt flood runoff practically has not changed, while winter runoff has changed most significantly, as is also typical of the warm past epochs, considered here, in which the scale of changes in air temperature and atmospheric moistening was different.

Volga River Runoff in the Warm Climatic Epochs of the Geological Past, in the Periods of Instrumental Observations and the Scenario Future

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The features of the Volga water flow changes in the last interglacial climatic optimum (~125 ka BP), Holocene optimum, modern (starting from 1981), and scenario (2006–2039) global warming have been revealed. Paleoclimatic reconstructions based on data of spore and pollen analysis of fossil plants and results of calculations carried out on the ensemble of global climate models of PMIP-II program, as well as scenarios of climate warming, performed on an ensemble of global climate models of CMIP3 program, have been used. Hydrological changes have been evaluated on the basis of the monthly water balance model). The most notable hydroclimatic changes took place in the warm epoch of the last interglacial climatic optimum, when the annual river runoff was 25% less than its modern value. Scenario air temperature in the Volga basin for the first third of the current century was close to the temperature of the Holocene optimum, reconstructed on the basis of palynological data. At the same time, the simulated annual flow was lower than the modern one. At projected and the Holocene Optimum climatic conditions reconstructed within PMIP-II, it appears above modern. The most noticeable differences in the Volga flow in warm climate of the Holocene optimum, modern and scenario periods are manifested in changes in the intra-annual distribution of their water flow.

Keywords: the Mikulino interglacial climatic optimum, the Holocene optimum, modern global warming, the Volga

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