

Water Budget of the Caspian Sea in the Last Glacial Maximum by Data of Experiments with Mathematical Models

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Abstract—Variations of Caspian Sea water budget in the epoch of the Last Glacial Maximum (LGM, ~21 thousand years ago) relative to the preindustrial conditions (~1850 CE) are considered using data of climatic modeling under PMIP4-CMIP6 projects. The variations of evaporation from the Caspian Sea surface and the volumes of river flow required to maintain the equilibrium state of the lake under various climate conditions and under various lake levels were also evaluated with the use of a regional configuration of the eddy-resolving-oceanic model INMIO-CICE. The boundary conditions in the oceanic model were derived from experiments with INMCM climate model reproducing LGM climate and the climate of preindustrial period. According to the data of PMIP4 simulation, both Volga runoff and evaporation from the Caspian Sea surface decreased in LGM epoch compared with the control experiment. The difference between the estimates by different models is rather high: from –5 to –50% for the Volga, and from –2 to –20% for the Caspian Sea. Such results are not enough to make unambiguous conclusions about whether the position of the Caspian in the LGM period was regressive or transgressive; however, deep regression of the Caspian is excluded. Even if the Caspian level is estimated with the use of the results of the model that has demonstrated the maximal decrease in the Volga runoff, the volume of river runoff from the territory of the Caspian basin will be enough to prevent the sea level dropping below –45 m above sea level.

Keywords: the Caspian Sea, paleoclimatic simulation, level variations, ocean general circulation model

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INTRODUCTION

Present-day paleogeographic data suggest wide variations of the Caspian level in the Late Glacial period; however, there still is no agreement about either dating or the possible mechanisms of these events [1, 3, 11]. In the opinion of Rychagov [6], the transgressive stage finished in the Late Pleistocene, and the Early Holocene was a period of regression. Svitoch [7] suggested that the transgression extended into the Early Holocene, and a drop started in the Middle Holocene. It is also worth mentioning that the extent of these variations is still to be specified. Most researchers agree that the amplitude of Caspian level variations in the Late Glacial was 30–40 m. The recent progress in the new data and methods suggests hope that the uncertainty in these direction will decrease [11, 12].

Some hypotheses explaining the considerable variations of Caspian Sea level are associated with climate variations in the Late Glacial. These include changes

in moistening conditions in the drainage basin, changes in runoff because of the formation of permafrost, and changes in the properties of soils, as well as the possible glacial runoff from the Scandinavian Ice Sheet. In this study, we used data of climate modeling under PMIP4 Project (Paleoclimate Modelling Intercomparison Project), to evaluate possible variations of the Caspian Sea level, associated with changes in moistening conditions in the Caspian basin in the epoch of maximum of the last glaciation (LGM, ~21 thousand years ago). Water balance components of the Caspian Sea were also evaluated based on data of paleoclimatic modeling for previous stages of PMIP project [4, 8, 9, 20]. The fundamental distinction of this study is the additional use of a high-resolution oceanic model, which improved the estimate of evaporation from the Caspian surface and the runoff volumes required for maintaining lake level at different marks, because no unambiguous data on the Caspian level during LGM are available now.

Table 1. Information about models

Model name (denotation in the article), reference	Number of cells (longitude × latitude)	Duration of the experiment, years	Reconstruction of glaciation used in the experiment	Dynamic vegetation	The Caspian Sea is specified as land/ocean
AWI-ESM-1-1-LR (AWI), [23]	192 × 96	PI—100 LGM—100	ICE-6G_C	Yes	Ocean
INM-CM4-8 (INMCM), [26]	180 × 120	PI—531 LGM—200	ICE-6G_C	No	Ocean
MIROC-ES2L (MIROC), [16]	128 × 64	PI—500 LGM—100	ICE-6G_C	No	Land
MPI-ESM1-2-LR (MPI), [22]	192 × 96	PI—1000 LGM—100	ICE-6G_C	No	Ocean

DATA OF CLIMATE MODELING

The analysis was focused on the results of experiments piControl (PI) and LGM (Last Glacial Maximum), performed under projects PMIP4 and CMIP6 [14], available in [17] (Table 1). PI (control experiment) was basic experiment with fixed concentrations of trace gases and aerosols gases, aerosols, and at pre-industrial level (about the year of 1850). LGM experiment reproduced the climate of the Last Glacial Maximum—a period with maximal volume of glacial cover (~21 thousand years ago) within the last glacial epoch 19–25 years ago). The key features of this experiment are the general increase in ice volumes, the appearance of glacial sheets in Eurasia and North America, sea level drop (by 115–130 m), and changes in land topography and configuration associated with them. The orbital parameters and the gas concentration of the atmosphere are also specified in accordance with reconstruction data. Several reconstructions of glacial sheets can be used in the experiment. The boundary conditions for LGM experiment are given in more detail in [19].

ESTIMATING WATER BALANCE COMPONENTS OF THE CASPIAN SEA

The Caspian Sea is a large drainless water body, the level of which is determined by the balance between river runoff and net evaporation (the difference between precipitation and evaporation) from its surface.

River Runoff

This study considers the runoff volumes of the Volga and other rivers of the Caucasian Region, because in total they account for >90% of river water inflow into the Caspian Sea, with the Volga accounting on the average for ~80% of the total runoff [10]. In this case, the authors analyze climatic runoff (the difference between model precipitation and evaporation) to evaluate changes in the moistening regime in the

Caspian basin and, directly, river runoff as an output parameter of the climatic model (Table 2). The use of model river flow alone in the estimate of Volga runoff can be not quite correct for this study as this variable in some models includes meltwater of the Scandinavian Ice Sheet, because, according to data of reconstruction of glaciation used in the model experiments, the northwestern part of the Volga basin is the periphery of the Scandinavian Ice Sheet. It should also be mentioned that not all models under consideration contain a dynamic block of vegetation and that the characteristics of the underlying surface for experiment LGM were specified the same as in the PI experiment. Changes in these parameters in LGM could have a considerable effect on the volumes of river runoff.

The Volga drainage basin was specified within its present-day boundaries for both PI and LGM experiments. At the interpolation of the boundaries of the basin onto model grids, the basin area was found to be greater than the actual value on the average by 20%; therefore, the comparison with observation data should be largely based on the river flow component given in Table 2 and converted into runoff depth (mm). All models demonstrated a decrease in both evaporation (21–50%) and precipitation (18–50%) in the Volga drainage basin; this resulted in a decrease in the climatic runoff (5–50%). In models AWI and MIROC, the deficiency of precipitation was practically compensated by a decrease in evaporation; therefore, the decrease in runoff was as little as 5%; this was not the case in INMCM and MPI, which led to a decrease in the runoff by half. The differences between the runoff depth, calculated as the difference between precipitation and evaporation, and the model river runoff were small, except for model INMCM, where the model river runoff was higher than its climatic value by 10 km³/year in the LGM epoch, which is due precisely to the contribution of glacial waters.

All models demonstrate maximal decrease of runoff depth in the northern parts of the Volga basin due to their closeness to the glacial sheet (Fig. 1), while the

Table 2. Variations of Volga runoff components by data of observations and PMIP4 simulation (mm—mm in the layer, % compared with the check experiment)

Data source	Period	Precipitation, km ³ /year	Evaporation, km ³ /year	Climatic runoff, km ³ /year	Model runoff, km ³ /year	Drainage area, km ²
Volga [10]		873 (642 mm)	621 (457 mm)	252 (185 mm)		1380000
AWI	PI	1028 (602 mm)	850 (497 mm)	178 (105 mm)	175 (103 mm)	1708500
	LGM	839 (491 mm)	670 (392 mm)	169 (99 mm)	166 (97 mm)	
	LGM–PI	–189 (–18%)	–180 (–21%)	–9 (–5%)	–9 (5%)	
INMCM	PI	1009 (568 mm)	748 (421 mm)	261 (147 mm)	262 (147 mm)	1776670
	LGM	495 (278 mm)	367 (206 mm)	128 (72 mm)	138 (78 mm)	
	LGM–PI	–514 (–50%)	–381 (–50%)	–133 (–50%)	–123 (–47%)	
MIROC	PI	1099 (650 mm)	874 (517 mm)	225 (133 mm)	222 (131 mm)	1692000
	LGM	776 (459 mm)	562 (332 mm)	214 (127 mm)	210 (125 mm)	
	LGM–PI	–323 (–29%)	–312 (–36%)	–11 (–5%)	–12 (–5%)	
MPI	PI	1293 (767 mm)	963 (571 mm)	330 (196 mm)	328 (194 mm)	1686000
	LGM	828 (491 mm)	674 (400 mm)	154 (91 mm)	151 (90 mm)	
	LGM–PI	–465 (–36%)	–289 (–30%)	–176 (–53%)	–177 (–54%)	

conditions in the Lower Volga and Caucasian rivers in the LGM can be even moister.

Water Balance on the Caspian Sea Surface

Another important component of the Caspian water balance, in addition to river runoff, is the evaporation from lake surface. In some global climate models, the Caspian Sea is specified as a *sea*, i.e., a system of oceanic equations is solved for the cells, and sea ice is forming there. In some models, the Caspian Sea is not specified in the mask as a *sea*, but is treated as land cells fully covered by water, i.e., in this case the internal dynamics of the water body is not taken into account, but only changes in the properties of land surface are considered, which is of importance for correct reproduction of the regional climate. However, in neither case the water balance equation is solved for the lake and its area does not change but is set constant at the beginning of the experiment and does not depend on river runoff volume and water balance on the surface. In addition, the spatial resolution of climate models is not enough to specify lake water area and bathymetry in sufficient detail. The low resolution leads to errors in the reproduction of three-dimensional circulation and the thermohaline structure of water, which determine the distribution and the total rate of evaporation from the sea surface. Therefore, to determine the scale of the Caspian Sea level variations requires a high-resolution model, which takes into account the morphometric features of the water body and can reproduce intense eddies and meridional overturning circulation, abrupt gradients of surface temperature, and the appropriate changes of heat fluxes between the sea and the atmosphere, coastal upwelling, and, at least in parameterized form, con-

vective mixing. The area of evaporation in the cold season and the duration of the open-water season in the warm period depends on the accuracy of the ice model and its interaction with the sea.

The estimates of the depth of evaporation from the Caspian Sea and the volumes of river flow required to maintain the equilibrium state of the lake under various climate conditions were improved with the use of the eddy-resolving oceanic model (INMIO) combined with sea ice model CICE.

The INMIO-CICE model approximates a system of three-dimensional equations of oceanic dynamics and thermodynamics in Boussinesq approximation, hydrostatics, and water incompressibility by finite volume method on a grid of *B* type in vertical *z*-coordinates. The numerical implementation of the model is described in [25]. In this study, a regular horizontal model grid with a resolution of 0.27° over the longitude and 0.2° over the latitude is used, which corresponds to the size of a cell of ~22 km at the latitude of the Caspian Sea. The time step is 20 min. The vertical discretization includes 28 horizons with a step from 6 m in the top layer to 125 m in the depth. The evaporation and surface turbulent fluxes of heat and momentum are calculated based on the values of the temperature and specific air humidity, along with wind speed with the use of bulk formulas [21]. The boundary conditions also include the precipitation intensity and the fluxes of incoming long-wave and short-wave radiation. The horizontal exchanges are described with the use of a biharmonic operator for the momentum and Laplace operator for the temperature and salinity with nominal (equatorial) coefficients of $-1.5 \times 10^{11} \text{ m}^4/\text{s}$ and $300 \text{ m}^2/\text{s}$, respectively. The model of ice dynamics and thermodynamics CICE [18] in zero-layer approx-

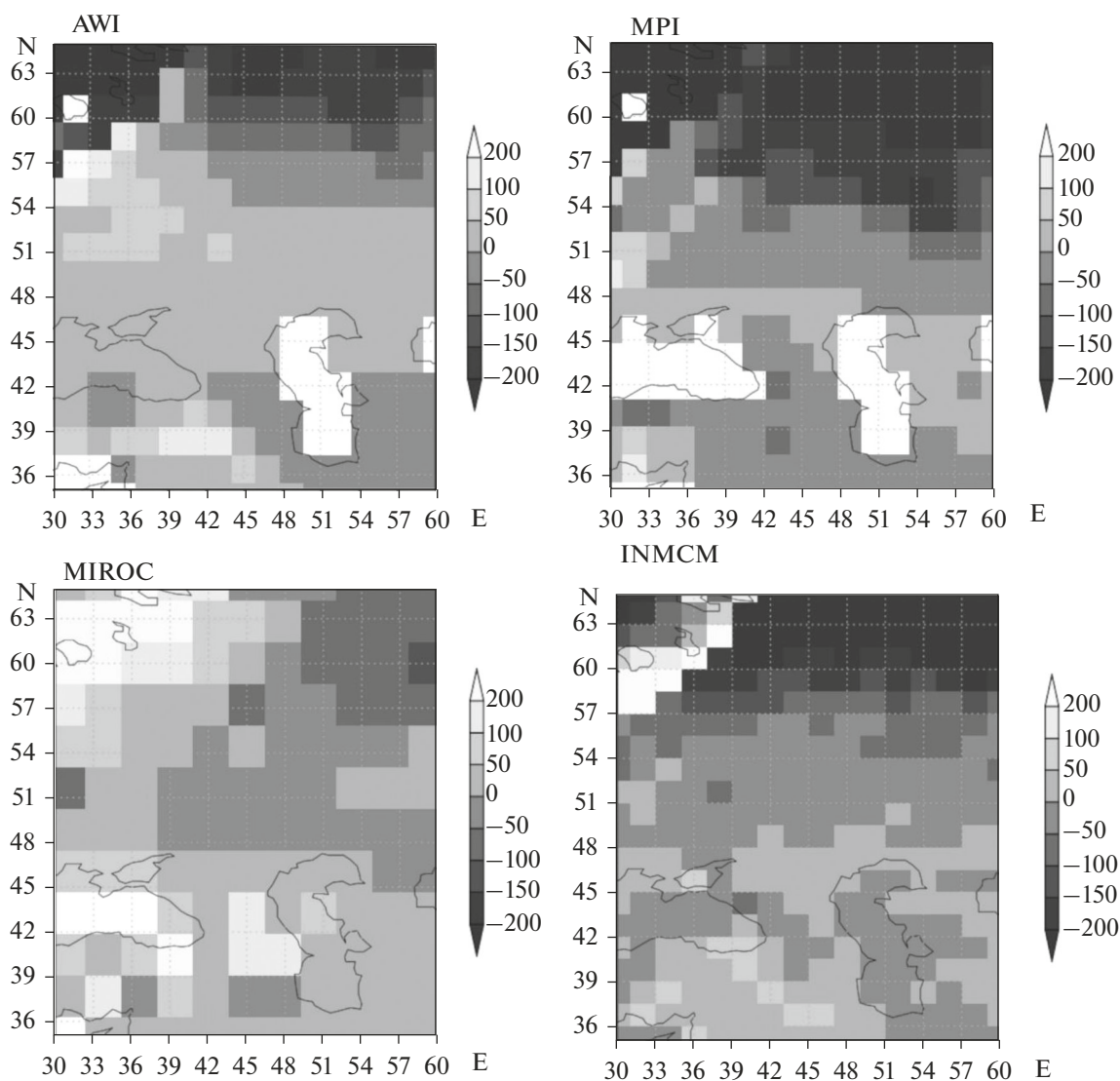


Fig. 1. Variations of river runoff (mm/year) in LGM epoch compared with the PI experiment by data of PMIP4 models.

imation is used on the grid with the same resolution and the same time step as the oceanic model. The structure of the INMIO-CICE model is described in [15].

The calculations were made for different Caspian levels: -60 , -45 , -30 , and -15 m above sea level (m a.s.l.) (Fig. 2). The meteorological forcing data were taken from experiments with INMCM model for reproduction of preindustrial climate and LGM climate with a daily resolution.

The experiment was organized as follows: at each lake level, an initial approximation was specified for the value of river runoff as an empirical linear function of the water area (in the case of experiment with a level of -30 m a.s.l. and preindustrial atmospheric conditions, it corresponds to observation data). Next, for a period of 20 years, calculations were made with the use of data of climate modeling INMCM (experiments

PI, LGM) to evaluate water disbalance averaged over years 6–20. Next, the volume of river runoff was corrected by the disbalance value and the calculations continued for 30 years more under the conditions of a balanced state of the Caspian. Finally, analysis was made of the obtained evaporation fields averaged over the last 20 years. The obtained volumes of river runoff required for a balanced state of the Caspian Sea at different levels for preindustrial climate and LGM climate are given in Fig. 3.

The above experiments provide estimates of the volumes of evaporation from Caspian surface under different climate conditions, which are more correct than those based on the data of global climate models. They also give the dependence of the evaporation volumes on the Caspian level, which is nonlinear because of the morphological features of the lake (a consider-

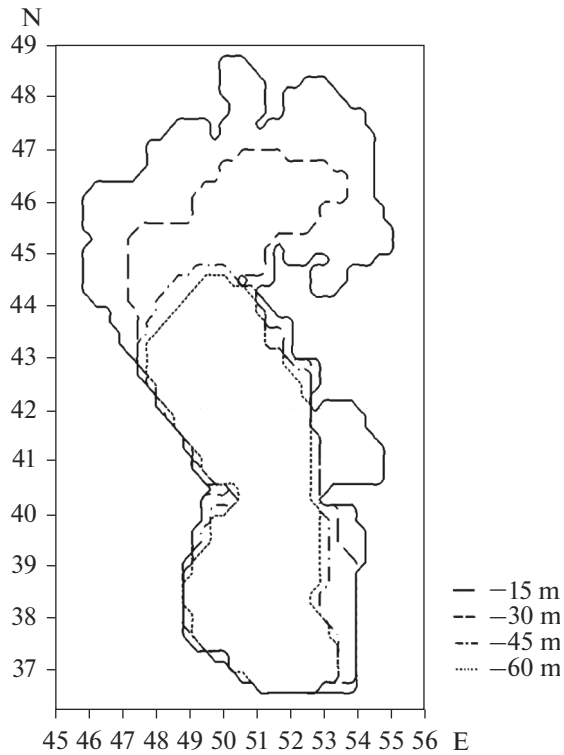


Fig. 2. Caspian Sea configuration in INMIO-CICE model for experiments with various sea level.

able increase in shallow-water area at a level above -30 m a.s.l.).

As can be seen from Table 3, most models demonstrate a decrease in evaporation from lake surface. According to modeling data, the mean annual temperature above the Caspian Sea in LGM was 5–7°C below its current values; accordingly, this resulted in a

shorter open-water period and a lower summer evaporation. Precipitation also decreased, but not much.

VARIATIONS OF THE CASPIAN LEVEL

The obtained dependence of the Caspian level on the volume of evaporation from its surface and equilibrium river runoff enables assessing the possible changes in its level in LGM epoch with the use of data of climatic simulation under PMIP4 project. The model results demonstrated a wide scatter: half of the models reproduced the Volga runoff close to preindustrial, while another demonstrated an increase by 40–50%. The obtained range of Volga runoff in LGM epoch in absolute values was 72–127 mm, which corresponds to 100–176 km³/year (converted to the drainage area of 1380000 km²). With changes in the LGM considered as a deviation from the modern observed runoff, the Volga runoff in LGM will be 125–240 km³/year.

We also are to take into account the runoff of the rivers other than the Volga. The Caucasian rivers (the Terek, Sulak, and Kura) bring ~30, and the Ural, ~8 km³/year [10]. Overall, these rivers, taken with the Volga, account for 95% of river runoff into the Caspian Sea [10]. The absolute values of mountain river runoff in the global climate models are underestimated because it is impossible to fully take into account the orographic factor (low resolution, hydrostatic approximation); therefore, it is reasonable to consider relative changes in runoff volumes in the region, which are ≤20% for all models, i.e., the total runoff of Caucasian rivers varies within the range 25–35 km³/year, and most models show even an increase in their runoff in this region. Thus, the minimal estimates of river runoff into the Caspian Sea are ~145, and the maximal, ~280 km³/year. According to calcu-

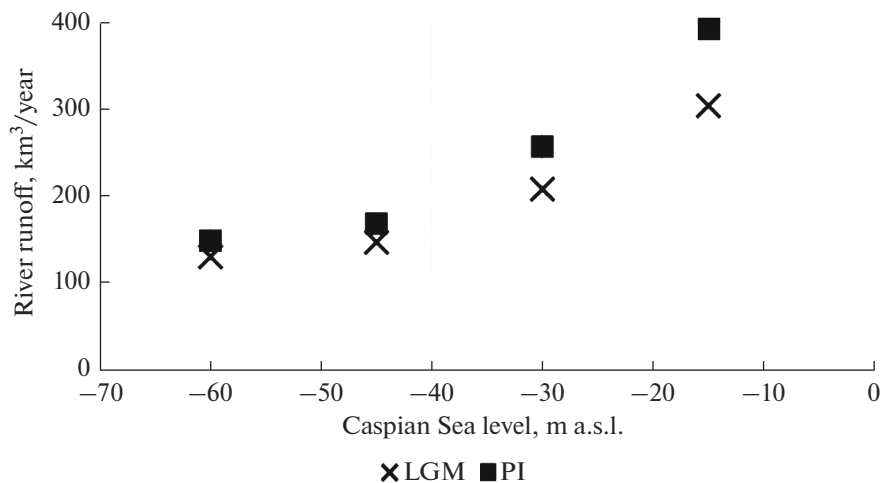


Fig. 3. River runoff volume required for the equilibrium state of the Caspian Sea at different levels for preindustrial climate and LGM by data of INMIO-CICE and INMCM.

Table 3. Precipitation and evaporation over Caspian territory by simulation and observation data

Data source	Experiment	Precipitation, mm/year	Evaporation, mm/year
AWI	PI	188	1124
	LGM	178	1065
INM-CM48	PI	248	1044
	LGM	204	1022
MIROC	PI	438	836
	LGM	356	673
MPI	PI	249	1114
	LGM	241	936
INMIO-CICE + INM-CM48	PI	248 (INM-CM48)	918
	LGM	204 (INM-CM48)	760
Observations [2]	—	215 ± 50	980 ± 20

lations with the use of INMIO-CICE model, these volumes of river runoff in LGM correspond to Caspian levels ~ -45 and ~ -20 below sea level.

In addition to the climate river runoff, a component of Caspian water balance could be the runoff of the glacial meltwater from the Scandinavian Ice Sheet, the boundary of which lied in the Upper Volga. The melting depth was not evaluated separately by modeling data. The runoff depth in the cells of INMCM model in sheet periphery was 600–800 mm/year, it was not calculated in models MPI and AWI. Based on estimates in [5, 24], we take the volume of meltwater entering the Volga to be ~ 50 km³/year; in that case, the possible range of Caspian level variations is from slightly below -30 m a.s.l. at minimal to > -15 m a.s.l. at maximal estimates of river runoff volume (additional experiments with INMIO-CICE model are to be carried out for Caspian level > -15 m a.s.l. in order to improve the estimate of the highest Caspian level).

CONCLUSIONS

The small number of models and the considerable scatter of the values of Caspian water balance components between the models make it impossible to unambiguously determine what was the phase of the Caspian Sea in LGM period—transgressive or regressive. All models demonstrated a decrease in both precipitation and evaporation in the Volga basin in LGM epoch, in some models the decreases in these components compensated for one another and the runoff practically did not change, while in other models, this resulted in a decrease in the runoff by half. In the drainage basins of Caucasian rivers (the Sulak, Kura, and Terek) the moistening conditions in LGM have changed only slightly, most models even showed a small increase in the runoff depth. The calculation of the volume of glacial runoff from the Scandinavian Ice Sheet introduces additional uncertainty to the estimates of the total volumes of flow into the Caspian Sea

in LGM period. The melting depth was not calculated in this study; this should be made in the future with specification by paleogeographic data on the possible domains of the glacial sheet, from which water recharge into the Volga was taking place. The causes mentioned above do not allow unambiguous conclusions to be made about the position of the Caspian in LGM period; however, the obtained results very likely exclude the deep regression of the Caspian Sea. Even for the estimate of the Caspian level with the use of INMCM model results, which demonstrated maximal decrease of the Volga runoff, the volume of river flow from the Caspian drainage basin will be enough to prevent the level of the Caspian Sea from falling below -45 m a.s.l.

The volumes of evaporation and river flow required to maintain the equilibrium state of the Caspian Sea at different levels and under different climate conditions, obtained with the use of a high-resolution oceanic model, reproducing three-dimensional circulation in the water body and ice dynamics, can be of use for estimating model results and paleogeographic reconstructions. Note that the volumes of equilibrium river runoff differ considerably for the modern climate and LGM climate, especially, for the Caspian level higher than the present one. In the future, additional experiments are planned for the Caspian levels below -15 m a.s.l.

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