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THE CURRENT STATE AND THE PROSPECTS OF RIVER MOUTH HYDROLOGY: TO THE 90TH ANNIVERSARY OF V. N. MIKHAILOV

Assessment of Influences of Anthropogenic and Climatic Changes in the Drainage Basin on Hydrological Processes in the Gulf of Ob

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Abstract—Changes in the runoff of rivers flowing into the Arctic Ocean caused by climate changes and increasing anthropogenic load lead to foreseeable transformations of hydrological processes in the mouth areas of the rivers. Climatic, water-balance, and hydrodynamic models were successively applied to evaluate the effect of climatic and anthropogenic changes in the drainage basin of the Ob river estuary on seasonal hydrological processes in the Gulf of Ob. Climate changes along with considerable seasonal redistribution of river runoff in the drainage basin of the Gulf of Ob, mostly due to its increase in winter, were found to cause no significant changes in the seasonal hydrological mouth processes in 1980–2018. Estimates for a period of up to 2050 showed that climate changes under various scenarios will cause an increase in streamflow from the basin, which will reduce the penetration of saltwater into the gulf.

Keywords: the Gulf of Ob, seasonal hydrological processes, drainage basin, economic activity, climate changes

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INTRODUCTION

The mouth areas of rivers in the Arctic zone of the Russian Federation now are of special interest in the context of water supply to the population and the developing economic activity. Changes in of the hydrological processes in estuaries, include the position of frontal zone, the depth to the halocline, water level variations, convection depth, ice phases, and other characteristics, which have their effects on both the biotic components of the ecosystem and the appropriate branches of economic activity.

The Gulf of Ob is a critical natural and economic resource for the stable and sustainable development of the most rapidly developing economic region of the Russian Arctic. However, the poor hydrological knowledge of this region, inadequate observation system, and the lack of reliable forecasts of changes in the hydrological processes in the Gulf of Ob under the effect of external factors increase the risks of adverse effects for the entire regional water-management complex. The natural and anthropogenic changes in the drainage areas of large rivers flowing into the Arctic Ocean have their effect on the hydrological processes in the mouth areas of rivers and nearby marine water areas through water, heat, and sediment fluxes. In particular, considerable changes were recorded in the recent decades in the drainage basin of the Gulf of Ob. These include changes in the volume and the annual distribution of river flow [27, 39], thermal and ice regimes of rivers [30, 38, 51], draining of thermokarst lakes [40, 44], permafrost thawing [34, 42], and the growing water consumption, especially, in the southern parts of China and Kazakhstan [8, 21]. No doubt, the processes in the drainage basin mentioned above, along with considerable changes in the climate characteristics over the Gulf of Ob and its watershed, affect various hydrological processes in the gulf. Note that the data of ground and satellite observations of the hydrological and meteorological characteristics and the underlying surface in the regions are very limited and not enough for detail analysis of long-term hydrological changes in the Gulf of Ob. Therefore, the best way to evaluate the current changes in various hydrological characteristics in the Gulf of Ob and to reveal the main contributing factors is the use of a system of mathematical models taking into account regional climate changes as well as the hydrological and anthropogenic processes in the drainage basin and in the Gulf of Ob itself.

Under the current intensification of economic activity in the mouth areas of Russian Arctic rivers it appears promising to assess the possible changes in the conditions of mouth systems through analysis of a system of hydrological parameters, taking into account their specific features.

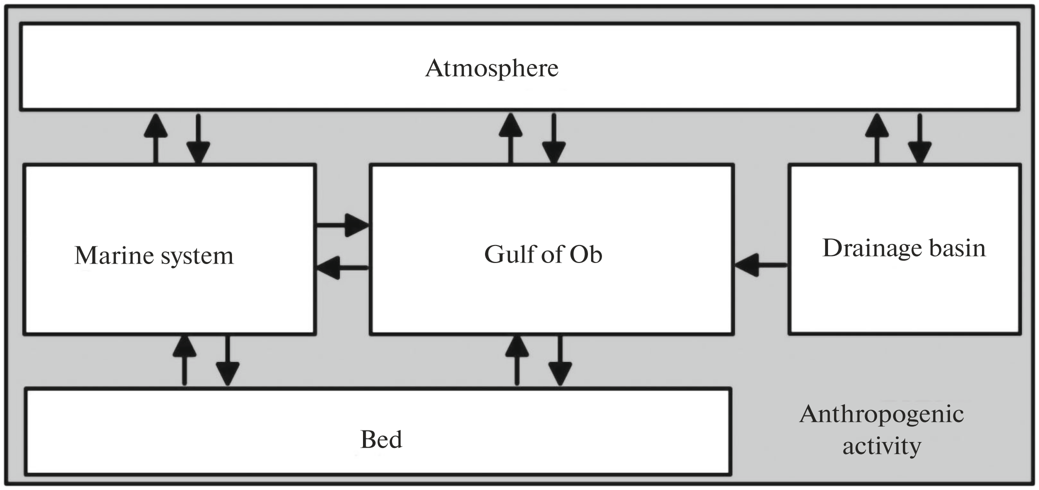

Fig. 1. Schematic effect of external factors in the Gulf of Ob.

The Gulf of Ob stands out of other large estuarine objects of the Russian Arctic by the presence of most large-scale projects for the development of hydrocarbon deposits in the coastal territory, the construction of large plants for hydrocarbon processing, and new port facilities for product transportation. A specific feature of its regional economy is a combination of two economic structures, i.e., conventional and industrial [16]. In this context, changes in the hydrological processes in the gulf can have an effect on the environmental conditions of the gulf and on different aspects of the economic and social sphere. The mouth processes are subject to the effect of the external systems of the river, sea, and atmosphere and they are governed by the natural and anthropogenic factors [11].

This study provides an estimate of the current and anticipated changes in the hydrological processes in the Gulf of Ob under the influences of climate changes and other natural and anthropogenic factors that are forming in the river basin, based on multimodel experiments with the use of a regional climate model, a hydrological model of the watershed, taking into account the economic activity, and a three-dimensional hydrodynamic model of the Gulf of Ob.

THE METHODOLOGICAL APPROACH AND THE MODELS USED IN THE STUDY

The climatic and anthropogenic changes in the drainage area affect the mouth processes via the river flow that forms in such area. The characteristics of river flow in the Gulf of Ob watershed show distinct seasonal variations with a pronounced spring–summer flood (mostly due to snow melting), summer–autumn low-water season with periodic rain floods, and a long winter low-water season. The analysis of long-term variations of the runoff of large rivers flowing into the Gulf of Ob shows a minor increase in the annual runoff [39] and a considerable increase in in winter streamflow [43], as is also typical of other rivers in the Arctic basin [39, 46].

River runoff transforms in the mouth reach from the outlet section in Salekhard C. to the Gulf of Ob, i.e., to the delta coastline. River flow takes place from a local drainage area of the mouth domain, including the basins of the rivers of Nadym, Pur, Taz, and others, which flow into the gulfs of Ob and Taz. The waters of the river and the sea with different physicochemical properties dynamically interact in the estuary. The key hydrological mouth process is the penetration of salt seawater over hundreds of kilometers into the gulf, where it affects the dynamic, thermal, and ice conditions. The interaction between fresh and sea water, accompanied by the formation of vertical and horizontal salinity gradients is the main characteristic of the Gulf of Ob ecosystem. The Gulf, as well as the marine system and the drainage basin, are subject to the effect of heat and mass exchange with the atmosphere. The lithodynamic processes that take place in the gulf and nearby sea areas change the contours of the shore and the underwater relief. All elements of the system suffer from direct or indirect anthropogenic effects. The general scheme reflecting the effects of external factors on the ecosystem of the Gulf of Ob is given in Fig. 1.

The available data of the coastal hydrometeorological network cannot give a complete picture of the characteristics of the hydrological processes taking place in the Gulf of Ob [4]. Remote sensing methods (ice aerial reconnaissance, aerial thermal surveys, satellite images) give more detail data on the conditions of mouth area surfaces; however, information on many processes can be obtained only by sounding water mass during expedition studies. The existing field data on the processes of interaction between sea and river water in the bay are not enough to evaluate their seasonal characteristics, because changes in thermohaline fields between surveys is unknown as well as, to what extent the distributions of temperature and salinity, recorded by observations, reflect the seasonal variations of these fields and the limiting states of the system. Vast water areas are between the measurement points, and the hydrological regime in such areas can be evaluated only based on data available on their boundaries. The complexity of the processes taking place in river mouth areas, their large space and time scales, the fragmentary character of the field data, especially in transitional periods, make it impossible to use simple interpolation method (e.g., linear), and require the use of hydrodynamic modeling. The state and the development of the technologies applied for the operational monitoring of hydrological processes in the mouth areas of Arctic rivers under runoff regulation and climate changes are assessed in [18]. Numerical modeling of hydrological processes in the Gulf of Ob was more active in the recent years because of the need to assess the effect of the approach channel constructed on the sea bar [2, 3, 6, 20]. Commonly, a single annual cycle is simulated for different boundary conditions taking into account the tidal and synoptic processes.

To study the effect of climatic and anthropogenic changes in the drainage basin on the hydrological processes in the Gulf of Ob, it is proposed to simplify the system given in (Fig. 1) and to replace the real natural objects by their model representation.

When studying the effect of seasonal and long-term changes in river runoff on the mouth processes, it is reasonable to exclude from consideration the hydrophysical processes that can hamper the reliable interpretation of model calculation results: channel processes, the anthropogenic activity in the gulf, variations of the mean sea level, year-to-year variations of water thermohaline structure at the marine boundary of the gulf under the effect of the marine system, as well as short-time changes due to tidal and synoptic phenomena, since the processes of the annual (seasonal) variations fully determine the structure of water in the Gulf of Ob and form the background against which water structure variations at lesser time scales can be seen [4]. At this stage, the processes of transport and transformation of suffocation water in the Gulf of Ob are also excluded from consideration.

Now, with the system at the seasonal time scale limited to the processes of dynamic interaction between river and sea waters and mixing of river and sea water, the main elements of the system are water level, flow velocity, and water density, which is determined by the temperature and salinity. The main factors of river system are streamflow and water temperature, and those relating to the sea are seawater salinity and temperature. The effect of the atmosphere includes the dynamic impact on the top water layer and the temperature of water, which freezes up at cooling to the freezing point to form ice, isolating the bay water mass from the fluxes of heat at the water–atmosphere interface.

Spatially, the system is limited by the shore contour, free water surface, and the bed, as well as boundaries from the side of the river and the sea. As the system does not take into account the channel processes, the bed surface and shore contours are assumed constant.

The Hydrodynamic Model of the Gulf of Ob

To improve the accuracy of the interpolation of hydrological fields within the Gulf of Ob based on scarce observation data and model estimates on the gulf boundaries, a three-dimensional hydrodynamic model developed in the Princeton University [22] was used; the model takes into account the presence of circulation associated with density heterogeneity and stable stratification, the presence of appreciable long-period (gravity) level variations with the amplitude compared with the depth. Seasonal hydrological processes are simulated taking into account the processes of the formation and melting of ice, the thickness of which is also comparable with the depth [17].

The experience of simulation of hydrological processes in the Gulf of Ob for assessing the effect of the approach channel in the gulf on its state shows that a fine grid cell resolution leads to an increase in the computing time, thus hampering the simulation for a long period [2, 6]. Therefore, the Gulf of Ob was simulated in this study on a grid with cells 4 × 4 km, which can reproduce seasonal hydrological processes and their year-to-year variations for practically all water area of the Ob and Taz gulf with the least computation times. With this size of the cell, the areas containing less than three grid nodes were excluded from the model domain. As the result, the grid covers the Gulf of Ob from the delta coastline to the exit into the sea (the section Vil'kitskogo Isl.–Belyi Isl.) and Taz Bay from Nakhodka Settl. to the confluence with the Gulf of Ob. Along the vertical, the model domain is divided into 20 layers from the bed to water ice surface or to the bottom surface.

To satisfy the boundary conditions on the marine boundary of the model domain, averaged distribution of water temperature and salinity are specified using data of long-term measurements at the section Vil'kitskogo Isl.–Belyi Isl. in summer and in winter. The boundary conditions from the side of the river are specified in the form of water discharge and temperature with a step of 1 day. The flow of the large rivers of Ob and Nadym is specified on sections passing along delta coastlines, and the joint flow of the Pur and Taz rivers is specified on a section at Nakhodka Settl. In the case of a river emptying in the form of a wide flow, embracing several grid nodes, the water flow at the riv-

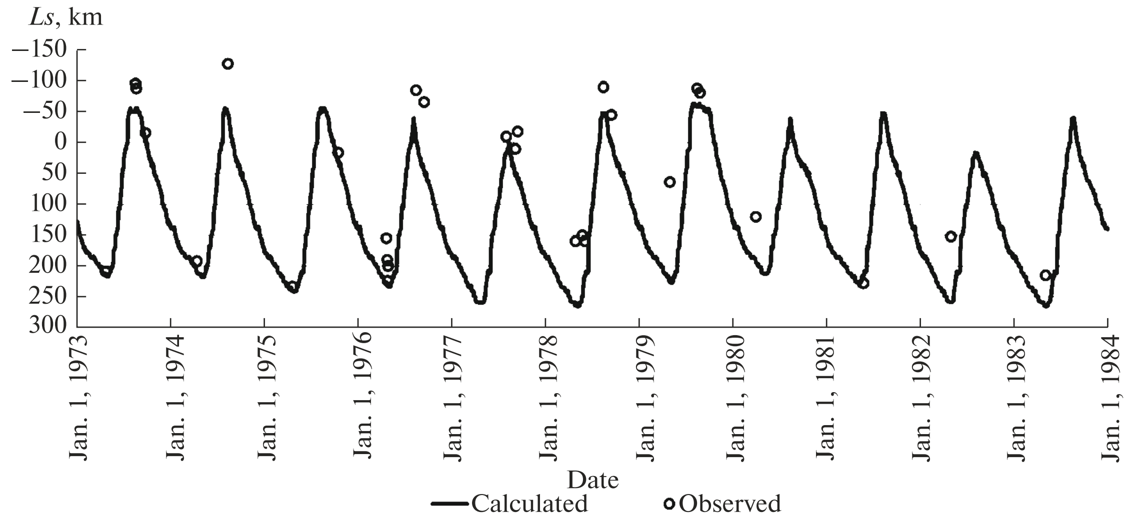

Fig. 2. Seawater penetration distance *Ls* (by isohaline 1‰ at the bed) into the Gulf of Ob by data of simulation and observations. The distance is measured from abeam Tambei Settl.

erine boundary of the model domain is distributed between grid nodes in proportion to the depth.

Field data on water discharge are available at the outlet sections of rivers lying some distance upstream of the boundary. River runoff undergoes some transformation within the mouth reach, determined by both the travel time and the lateral inflow. The water discharge was recalculated from the outlet section to the delta coastline with the use of a flow transformation model [14], based on Kalinin–Milyukov method [10], the parameters of which were chosen in accordance with recommendations given in [15].

The flow of small and medium-size rivers from the local watershed was also specified at the sites of their inflow into the gulf. Data on water temperature were specified in the same sections. As there are almost no field data on the flow from the local catchment of the Gulf of Ob, such data were derived from flow simulation on a water-balance model, which is discussed below. The spatial resolution of this model enabled to simulate the flow of 196 watercourses, which flow directly into the gulf, besides the large rivers of Ob, Nadym, Pur, and Taz [4], and totally accounting for the flow from 96% of the unmonitored part of the basin. Although the flow from the unmonitored part of the basin is ≤10% of the mean annual river inflow it plays an important role in summer, when its contribution can be as high as 15%. Therefore, the water and heat flow of small rivers has also to be taken into account to more reliably simulate the hydrodynamic processes in the Gulf of Ob.

The fluxes of heat and momentum at the atmosphere–water and atmosphere–ice interfaces are calculated using the data of standard meteorological observations at the coastal hydrometeorological network or using simulation data.

The three-dimensional hydrodynamic model of the Gulf of Ob was tested on the data of AARI multipurpose expeditions in the 1970s–1980s along with data of the coastal observation network. The period from 1976 to 1983 is best provided with data on the boundary conditions for model calculations. For this period, chosen for model testing, the most complete data are available on the hydrological fields and their dynamics within the domain and on its boundaries. The set of the states of the hydrological system in this period is representative enough. In terms of water volume in the inflowing rivers in this period, we can identify the low-water year of 1977 and the high-water year of 1979. Early springs were observed in 1976 and 1977 with accordingly early breaking up of the ice cover. The spring was cold in 1978 (air temperature was 2–3°C below the mean value) and 1979, when the break up of ice cover was later. A cold autumn with early freezing of the gulf was in 1976 and 1977.

Figure 2 demonstrates the simulated intrusion of seawater *Ls*, determined by 1‰ isohaline at the bed in the Gulf of Ob, compared with observation data. The calculations are in general agreement with the observation data. Note that the observed *Ls* has very large error, because the distance between the sections is on the average >50 km, the measurements at the sections were made successively (not synchronously), and the observations were carried out in different phases of the surge phenomena and tidal cycle. However, these are the only systematic, to some extent, observations of *Ls* in the Gulf of Ob, in addition, performed in an annual cycle, including periods of its maximal development.

Hydrological Model of the Catchment Basin

The inflow of river water into the Gulf of Ob, including that via small and medium-size rivers, was evaluated using the hydrological model WBM (Water Balance Model), developed in the University of New Hampshire (USA) [50]. Various modifications of this model are used in projects in the US and Russia, for example, to evaluate the water and carbon runoff in Alaska rivers [33], to forecast the runoff of large Arctic rivers [36, 40], to make a short-term forecast of the river and heat inflow into the seas of the Northeastern US, and to evaluate the effect of economic activity on river flow in different regions of the world [24, 53]. Its important advantage consists in that it takes into account the effect of economic activity in the catchment area (channel regulation, irrigation, municipal and industrial water consumption, as well as interbasin transfers of flow), which is important for the Ob basin. In addition, all software components of the WBM model will be published as open access in the Internet at the end of 2022 along with a detail description of their application. Other hydrological models, developed in Russia, e.g., ECOMAG [31] or Gidrograph [49], are not available in open access, require considerable preliminary preparation and adjustment, the use of additional input data for parameterization and validation, and do not fully take into account the economic activity in the catchment. The hydrological water-balance model WBM is a grid-cell model, reproducing the vertical water exchange between the atmosphere and land surface and the horizontal transport of river flow in channel network. To evaluate the contributions of different components responsible for river flow generation, the hydrological model WBM is functionally extended with a special block, which evaluates the major hydrological components of river runoff (groundwater runoff, snowmelt runoff, rainfall runoff, and glacier runoff) and their transformations along the channel network, as well as to evaluate the water storages in the soil, lakes and reservoirs. The evaluation of the runoff from glaciers in the WBM is based on calculations by a separate model of glacier runoff [28, 35]. To perform the simulation of water exchange between soil and subsoil water, a new algorithm MODFLOW was introduced in the model; this algorithm is an up-to-date block for the calculation of groundwater recharge, developed by USGS. In addition, to improve the calculations in mountain regions, a new component was introduced into WBM to take into account changes in snow storages with changes in elevation within a single grid cell based on high-resolution data on land topography. The thermal runoff is evaluated in WBM by an additional block for simulating water temperature based on the method given in [45].

In addition to the simulation of the natural hydrological regime, WBM can also take into account the effect of different types of economic activity on the hydrological characteristics, including the anthropogenic factors that are of greatest importance for the studied watershed, i.e., river runoff regulation by reservoirs and dams [50], water use for irrigation [24, 25], runoff diversion between river basins [52]. To evaluate the effect of local economic activity on river runoff in the studied watershed, the inflow of river water, and the thermal runoff into the Gulf of Ob, the calculations on WBM model were carried out for natural hydrological conditions and for antropogenic conditions when human activity was taken into account, including runoff regulation by reservoirs, irrigation, municipal and industrial water use, as well as water intake into the Irtysh–Karaganda canal. All calculations in WBM were carried out for daily time intervals for river network with a spatial resolution of 10 × 10 km. The evaporation and transpiration were calculated using Penman–Mantiss method, which most reliably accounts for the evapotranspiration from the underlying surface in regions with insufficient moistening and active land use, of which the southern part of the drainage basin of the Gulf of Ob is a part. The simulation of river flow transformation in the channel network was made using the method of linear reservoirs with a variable travel time function depending on runoff volume. This considerably improved the model results.

Regional Climate Model

The climate conditions in the drainage basin of the Gulf of Ob were analyzed with the use of the regional climate model WRF (Weather Research and Forecasting), which is widely used in the world for weather forecasts [32]. This model was adapted for the study area, including the drainage basin of the Gulf of Ob and the nearby regions. WRF is an up-to-date regional modeling system, containing all components required for the reproduction of the dynamics of the atmosphere [41]. The polar version Polar WRF (version 3.5.1), optimized for the Arctic and developed in the Polar Center for Climate Studies in the University of Ohio [26] was used for the region. The model Polar WRF includes modernized physical schemes of terrestrial and oceanic parameterizations of the surface layer, adjusted specifically for the Arctic. The boundary conditions for the WRF model were specified from the reanalysis NCEP/NCAR [29]. The calculations on the model were made with a spatial resolution of 30 × 30 km. The model calculations were carried out for the period of 1979 to 2018. The deviations of the calculated WRF fields from the results of observations and reanalysis were corrected according to the procedure described in [23]. Although this climate model calculates many various parameters of the atmosphere at different heights, only data of the surface layer were used in this study.

The results of model calculations on WRF and WBM are presented in the form of maps available through a regional online-system for Northern Eurasia [48], developed at the University of New Hampshire.

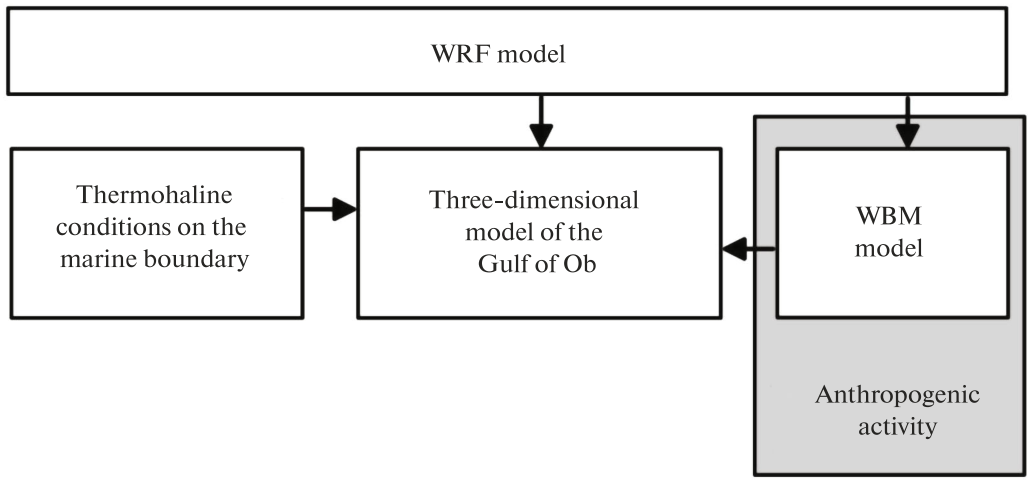

Fig. 3. Scheme of modeling seasonal hydrological processes in the Gulf of Ob.

Thus, the scheme of the influence of external factors on the system of the Gulf of Ob, given in Fig. 1, has been transformed for this study into the scheme of interaction between mathematical models for various purposes (Fig. 3).

MODEL EXPERIMENTS AND THEIR RESULTS

As noted above, calculations on WRF climate model were carried out for the period from 1979 to 2018 with the aim to assess the changes in the climate characteristics in the region and to obtain input data for hydrological models of the drainage basin and the mouth area. Figure 4 shows variations of the normal annual air temperature and precipitation over period 1980–2018 according to WRF data, calculated based on the slope of the linear trend. We have to note a small decrease in the normal annual air temperature (–0.6...–1.0°C over the entire period) in the central part of the Ob drainage basin and the very uneven variations of the annual precipitation with a trend toward its decrease in the western part of the region and in the northern part of Gulf of Ob along with its increase in the basins of the Irtysh and the middle Ob. Such heterogeneity in the trends of annual precipitation in this area explains the minor increase in the Ob river flow over this period compared to other large Arctic rivers [39].

To evaluate river inflow into the gulf of Ob over 1980–2018, calculations were made for the entire drainage basin of the Gulf of Ob on WBM model using WRF climatic data for two variants—with economic activity taken and not taken into account. Overall, WBM model gives an acceptable estimate of the river inflow into the Gulf of Ob with the use of climate data from WRF for small and medium rivers, although it overestimates the runoff of the Ob by ~25% relative to the observed values (Fig. 5). However, the simulated normal annual water discharge of the Ob shows a good correlation (0.75) with the observational data. Note that the overestimate of runoff by model calculations is mostly due to the overestimated precipitation, especially in summer, at the use of WRF model with boundary conditions from NCEP/NCAR reanalysis. This problem for NCEP/NCAR reanalysis is well known and it is due to the overestimation of convective precipitation over land in NCEP model [37]. Therefore, to more accurately estimate the runoff characteristics, the simulated runoff values were corrected in accordance with observation data from the available hydrological gages. In addition, calculations were made on WBM with the use of other climate data from MERRA2 and ERA5 reanalyses. Comparative analysis showed that the agreement between the simulated and observed runoff values was best at the use of climate data from MERRA2 reanalysis.

In addition to the analysis of river water inflow into the Gulf of Ob, the results of calculations were used to evaluate the changes in various hydrological characteristics over the drainage basin. It was found that the basin of the Gulf of Ob shows a regularity of an increase in runoff in the eastern regions and its decrease in its central, most swampy, part as well as in the northern part in permafrost zone. This is primarily due to variations of total precipitation over basin territory (Fig. 4). The analysis of seasonal variations of river runoff showed that the tendencies toward an increase in the annual runoff are primarily due to the increase in runoff in the autumn–winter period, when it is mostly formed due to groundwater recharge. At the same time, the northern regions, bordering the Arctic Ocean, show a decrease in snow storage and spring flood runoff, which is, most likely, due to a considerable increase in the mean annual air temperature (Fig. 4) and a decrease in the proportion of solid precipitation in the region.

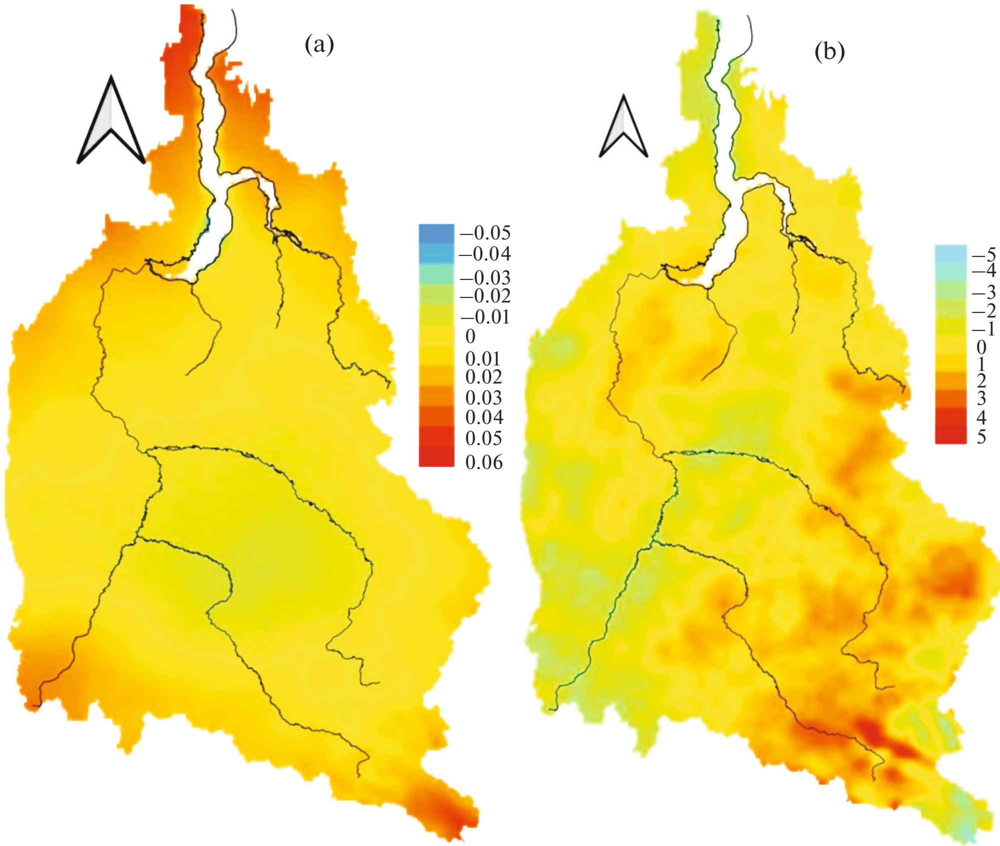

Fig. 4. (a) Linear regression slope of the mean annual air temperature, °C/year, and (b) the total annual precipitation, mm/year, over the drainage basin of the Gulf of Ob over 1980–2018 based on calculations by WRF regional climate model, determined by the slope of linear trend for each model grid with a resolution of 30 × 30 km.

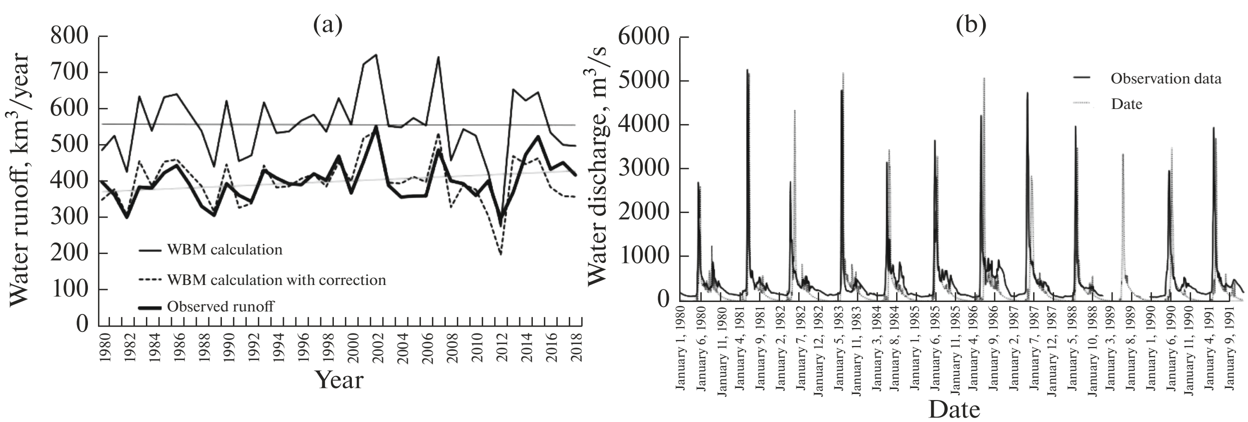

Fig. 5. Examples of WBM simulation of (a) the annual runoff of the Ob at Salekhard and (b) daily runoff hydrographs of the Nadym R. at Nadym with the use of meteorological data from regional WRF climate model and their comparison with observation data.

The comparison of calculation results for WBM with the effect of economic activity in the drainage basin taken and not taken into account has shown that the average annual runoff over 1980–2018 in the lower reaches of the Ob at Salekhard lacked on the average 18 km^3/year or <5% of the annual runoff due to anthropogenic factors. All large reservoirs in the basin are located in the upper reaches of the Ob and on its

Table 1. Projected changes in the mean annual runoff of large rivers flowing into the Gulf of Ob for two climate scenarios based on simulation on WBM model

Scenario/period	Ob R., Salekhard C.		Nadym R., Nadym Settl.		Pur. R., Samburg T.		Taz R., Sidorovsk Settl.	
	km^3	%	km^3	%	km^3	%	km^3	%
RCP 4.5 (2020–2040)	–6.1	–1.5	–1.6	–11	–3.2	–11	–0.8	–2.3
RCP 4.5 (2040–2060)	26.9	6.7	0	0	–1.4	–4.6	–0.2	–0.6
RCP 8.5 (2020–2040)	22.9	5.7	0.3	2.4	–0.6	–2.0	1.9	5.5
RCP 8.5 (2040–2060)	27.4	6.8	0.6	3.8	0.7	2.4	2.8	8.1

tributaries (the Irtysh and Tobol rivers) and have been constructed before 1980. Despite the high natural regulation of the Ob runoff, the large number of lakes and swamps in the middle and lower reaches of the Ob river resulted in that the regulation of runoff by reservoirs led to a considerable (by 20–25%) increase in winter runoff of the Ob at Salekhard and a minor decrease in the summer–autumn runoff. The effect of reservoirs on the spring flood runoff at Salekhard is not significant, because it mostly forms in the nonregulated part of the drainage basin.

The anticipated changes in the climatic characteristics in the drainage basin of the Gulf of Ob were evaluated using WRF model, in which the boundary conditions were determined by the global Atmosphere and Ocean General Circulation Model (AOGCM)—CCSMCommunity Climate System Model, which participates in Coupled Model Intercomparison Project Phase 5 (CMI5) [47]. The CCSM model was chosen because it in greatest detail takes into account the physical processes on the land, including hydrological processes, the effect of vegetation, and soil freezing. The calculations on WRF climate model were carried out for the basic historical period since 1979 to 2005 and for two scenarios describing the variations of the concentrations of greenhouse gases and aerosols under different variants of changes in the external radiation impacts RCP (Representative Concentration Pathways). In AOGCM, the change in the external parameters forecasted for the XXI century is specified taking into account four scenarios of anthropogenic impacts, constructed in accordance with the radiation flux at the atmosphere boundary expected for the year of 2100: RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5 (2.6, 4.5, 6.0, and 8.5 W/m^2). For the drainage basin of the Gulf of Ob, scenarios RCP 4.5 and RCP 8.5 were considered. To assess the future changes in various climate and hydrological characteristics, anticipated changes by 2030 and 2050 have been analyzed. To do this, the deviations of the mean values over periods 2020–2040 and 2040–2060 from the mean values over the basic historical period of 1971–2005 were compared. We project a further increase in the normal annual air temperature all over the drainage basin of the Gulf of Ob within the range from 1.5°C in its southern part to 4.5°C in the northern part according to RCP 8.5 by the year of 2050. According to this scenario, the annual precipitation will decrease considerably in the upper reaches of the Ob and slightly increase in the northern regions near the Gulf of Ob.

The climatic data for the future, obtained using WRF model, were used to simulate various characteristics of water balance over the drainage basin of the Gulf of Ob and to evaluate the river and heat inflow into the Gulf of Ob by calculations with WBM model. Figure 6 shows deviations of the mean annual runoff from its mean values over the historical period over the drainage basin of the Gulf of Ob for two scenarios of climate changes—RCP 4.5 and RCP 8.5. Note that the tendencies of changes in the annual runoff vary considerably depending on the climatic scenario used. The largest increase in the runoff (>50 mm/year) is expected in the western and central parts of the drainage basin, as well as in the Altai, according to scenario RCP 8.5 by the year of 2050. According to scenario RCP 4.5, a decrease in the runoff is expected in the lower Ob and in the basins of the Nadym, Pur, and Taz (down to 30 mm/year) and its considerable increase in the western part of the Ob basin by the year of 2050. Overall by both scenarios, a considerable increase in river inflow into the Gulf of Ob is expected by 2050, mostly, because of an increase in the Ob runoff (Table 1).

The results of model calculations with WBM were used to evaluate the river and heat flow from the territory not covered by regular observations, as well as to fill the gaps in data on river runoff at the outlet sections of large rivers.

The simulation of hydrological processes in the Gulf of Ob over 1980–2018 using a three-dimensional hydrodynamic model with the use of the results of calculations on WRF and WBM gave the following results.

The simulation of the level surface determined by river flow demonstrates a regular pattern of level decrease along the gulf from the delta coastline to the exit into the sea, and its results are in general agreement with the data of coastal observations, notwithstanding their poor quality [4]. The simulation shows the presence of lateral level denivelation, caused by the Coriolis force. The difference between the levels at the right and left banks, on the average over the gulf, is

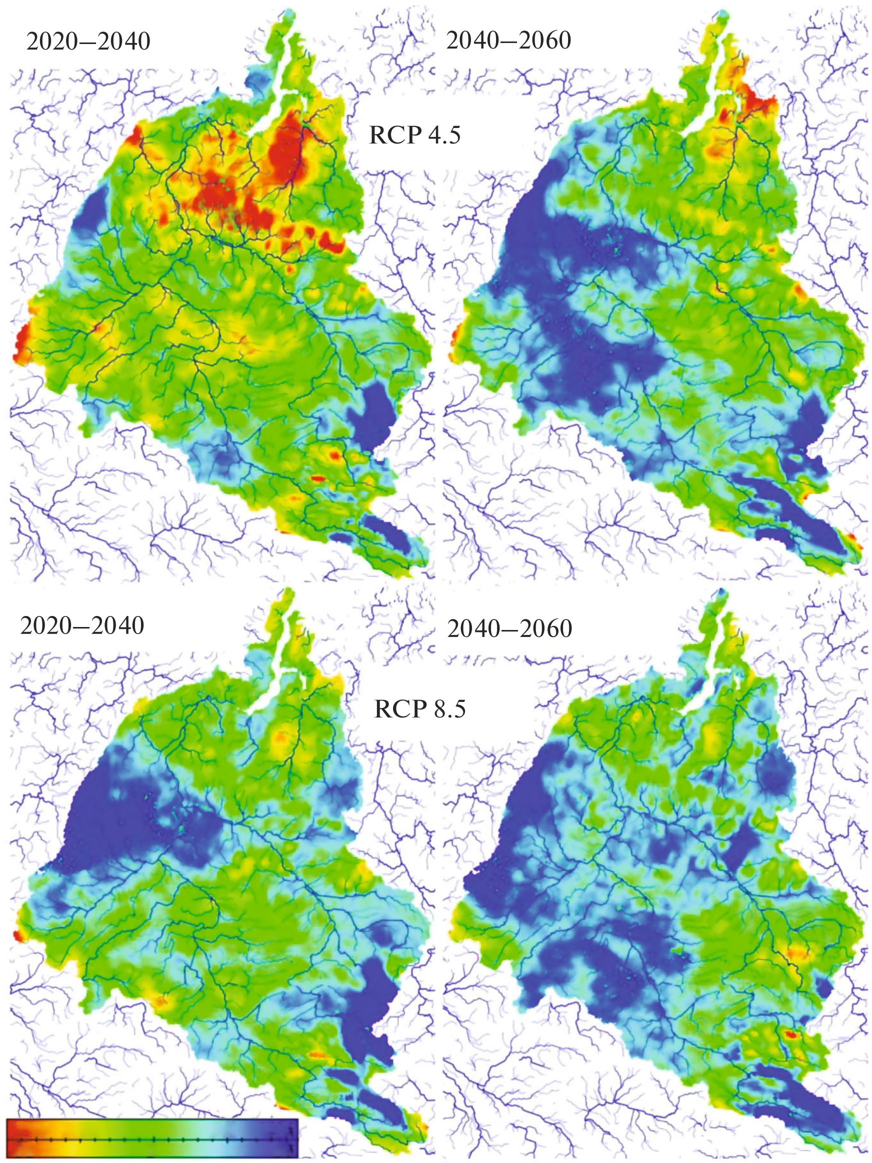

Fig. 6. Expected change in the mean runoff depth, mm, for the level of the years of 2030 and 2050, calculated by WBM for two climate scenarios RCP 4.5, RCP 8.5.

~2 cm in summer and ~0.5 cm in winter. As to the long-term variations of water level, it is difficult to compare the data of simulation and observations. As shown in [4], taking into account the state of the elevation base of gages in the gulfs of Ob and Taz, as well as not quite reliable quality of water level data, it is difficult, if not impossible, to make conclusions regarding the exact value of their long-term variation.

According to simulation data, the long-term variations of water level are insignificant all over the gulf. Long-term variations of water level are appreciable but statistically insignificant only near the mouths of large rivers: the level rises at the Ob mouth and drops near the mouths of the Nadym, Pur, and Taz.

The comparison of level fields simulated with the actual discharge hydrograph of the Ob and with hydrograph, calculated on WBM with economic activity not taken into account, showed a minor (below the accuracy of water level measurements at onshore gages, i.e., 1 cm) effect of economic activity in the Ob basin on water level in the Gulf of Ob. At the same time, the seasonal redistribution of flow by the hydropower stations now in operation leads to a drop (up to 4 mm) in the water level during summer practically all over the gulf, except for the zone near the hydraulic front north of Tambei, where the model shows a small level rise (up to 3 mm). In winter, river runoff redistribution has led to a level rise all over the gulf. The effect of this redistribution was largest at the

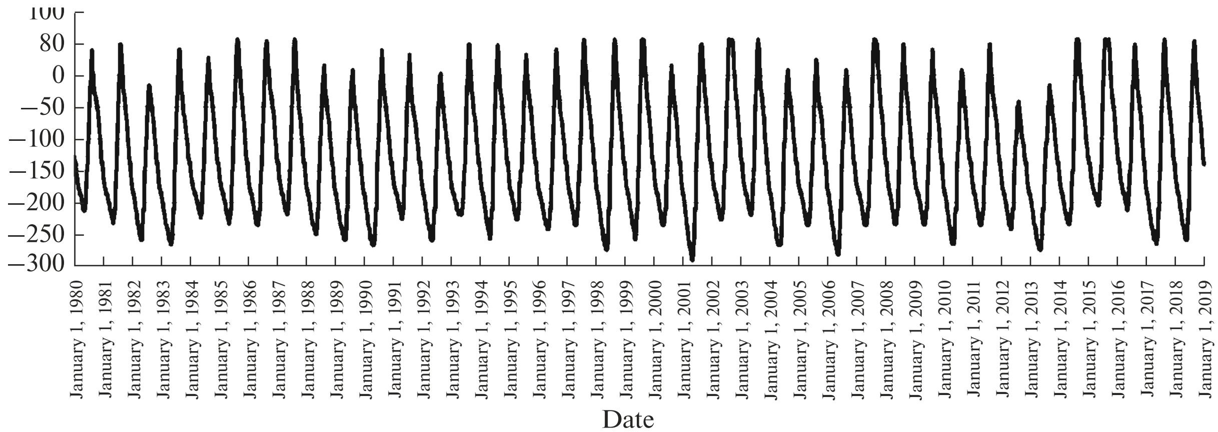

Fig.7. Estimated distance of seawater intrusion (by salinity 1‰ at the bed) into the Gulf of Ob over 1980–2018). The distance is measured from abeam Tambei Settl.

delta coastline and abruptly decreased toward the sea to disappear almost completely in the northern part.

The common drawback of the available observations for currents in the Gulf of Ob is their scatter over time and the incorporation of random situations. However, they provide a general picture of the character of currents in the gulf [9]. The currents in the northern Gulf of Ob are the vector sum of the discharge, wind surges, density, and periodic tidal components of flow velocity. While the variation ranges of tidal and synoptic velocities can be determined from irregular field data, the discharge components of the velocities are lesser and, therefore, more difficult to derive from the measured total velocities. The maximal values of discharge velocities occur at flood peaks, but, in such periods (during the destruction of ice cover), no measurements are carried out. Because of this, the range of the discharge component of flow velocities can be evaluated only with the use of a hydrodynamic model. According to model data for the period of spring flood wave passage, the discharge component of velocity is ~0.8 m/s at the riverine boundary of the model domain, it rapidly decreases at the nearshore, and abeam of Yam-Sale Cape it is not greater than 0.3 m/s. Further towards the exit into the sea, the discharge component of flow velocity can reach 0.2 m/s in some areas. During winter low-water season, the discharge component of velocity has maximal values at the riverine boundary and near halocline because of a decrease in flow cross-section, reaching 0.1 m/s. The density currents, which deliver seawater into the bay may reach 0.3 m/s in the periods of higher density gradients after flood recession, but commonly they have values up to 0.05 m/s.

The modeling has shown no considerable long-term changes in the discharge flow velocity all over the water area of the Gulf of Ob. However, minor changes can accumulate and manifest themselves as considerable changes of other hydrological characteristics, primarily, in the development of seawater intrusion into the gulf, which is determined by the proportions of the discharge and density velocity components.

An important characteristic, reflecting the overall changes in the hydrological fields in the mouth area under the effect of external factors is the distance of seawater intrusion *Ls*. The value of *Ls* in the Gulf of Ob, calculated over 1980–2018 is given in Fig. 7. The range of seasonal variations of *Ls* over this period was 350 km.

The *Ls* commonly reaches its maximum value in late April. The year-to-year variations of maximal *Ls* lies within the range from 204 to 290 km south of the beam of Tambei and shows no significant trend. The maximal *Ls* in the annual cycle mostly depends on the water volume in the previous period from August to April. The significant penetration of seawater into the gulf usually follows a period with lower river flow. In addition, it is also important the initial position of seawater front after the end of spring flood wave, which is mainly determined by the flood volume. The characteristics of ice cover also contribute to the propagation of the hydro-front through decreasing the flow cross-section and thus increasing the discharge component of the velocity. All these factors form a complex picture of hydro-front dynamics. Thus, at the maximal development of intrusion, which was simulated in 2001 (Fig. 8a), the previous period from August to April was not lowest streamflow over the studied period, and at the minimal development of intrusion, simulated in 2015 (Fig. 8b), the previous period was not greatest for river flow. This suggests that, in the case of the Gulf of Ob, which is a complex object, the simulations of individual years may not give the required result for identifying extreme hydrological situations [2, 6, 20], and model simulations for several years are necessary.

The maximal discharge of seawater from the mouth area under the effect of spring flood wave also shows

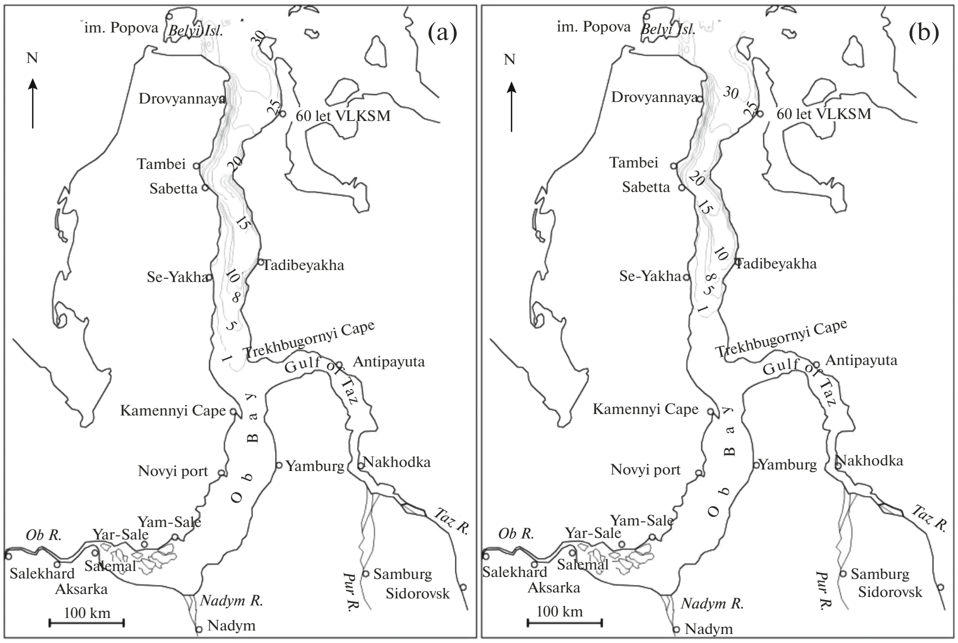

Fig. 8. Salinity distribution in the bottom horizon of the Gulf of Ob in the spring, ‰, (a) at the maximal development of seawater intrusion (2001) and (b) at the minimal development of such intrusion (2015) by simulation with specified actual flow of the Ob River.

year-to-year variations with a range of ~100 km and does not show significant trend. In this case, the hydraulic front runs on the average 35 km north of Tambei. In 2012 and 2013, because of the anomalously low flow of the Ob River, saline water in the bottom horizon stayed south of Tambei, which is confirmed by observation data [19].

Modeling with Ob flow hydrograph, calculated without taking into account the effect of economic activity in the river basin, has shown that, without runoff regulation by reservoirs, the model gives smaller maximal seawater inflow (up to 17 km), the forecasted maximal export of seawater is about the same as it is with the observed flow, and the slopes of linear regression trends of the maximal distance of inflow and the distance of seawater outflow change their signs (Table 2). This suggests that the economic activity in the river basin insignificantly compensates for the changes caused by natural factors.

The main regularities in the variations of water temperature in the area near the hydraulic front are generally the same as those for changes in water salinity. An integral characteristic of changes in the temperature distribution in the Gulf of Ob under the effect of changes in river flow can be the changes in ice characteristics induced by streamflow.

The simulated process of ice formation is in agreement with the general scheme of freezing of the Gulf of Ob, derived from the data of ice avia-reconnaissance of the 1970s and 1980s and observation data from the coastal network: the area that freezes first is the part of the gulf north of Tambei, shallow areas in the southern part of the Gulf of Ob, and the Gulf of Taz, as well as the shallow coastal areas; the central part of the gulf freezes the last [1, 4, 12, 13].

The results of processing data of the stationary marine coastal network in the Kara Sea over the past 30 years show that the time of ice appearance tend to shift by 3–4 day later, while in the XX century, such shift was 7–10 days; the time of ice disappearance, according to observations in the Kara Sea, tend to shift by up to 5 days earlier, while in the XX century, such shift was 5–12 days [7]. The results of simulations for 1980–2018 show a similar situation for the Gulf of Ob. On the average, the model yields a shift of the date of ice appearance by 5 days later over the study period. Such shifts are most considerable in the central part of the gulf from Trekhbugornyi Cape to Tambei, where the simulated shift over the study period reaches 16 days. On the average, the simulated date of ice disappearance shifts 11 days earlier over the model period. In this case, the shifts are most considerable in the northern part of the gulf. The contribution of river flow to the long-term changes in the dates of ice phases is insignificant. The changes are mostly due to the effect of atmospheric factors.

The effect of economic activity in the river basin on the time of beginning of ice phases is insignificant. The simulation with river flow calculated without taking into account the effect of reservoirs demonstrates a shift of the data of ice disappearance by 0.5 day later at the western coast in the central part of the gulf. The

Table 2. Characteristics of seawater intrusion in the Gulf of Ob by the data of simulation over 1980–2018

Boundary conditions	Observed runoff		Calculated runoff less the reservoirs	
intrusion characteristic	maximal inflow*	maximal outflow*	maximal inflow*	maximal outflow*
Maximal, km	–290	–41.6	–274	–40.8
Minimal, km	–204	56	–194	56
Range, km	86	98	80	96.8
Average, km	–243	35	–236	34
The slope of linear trend line, km/year	–0.14	0.03	0.07	–0.07

* from the beam of Tambei Settl. "–" toward the river, "+" seaward.

dates of ice appearance at the calculated runoff shift by 0.5 day earlier in some regions in the northern part of the gulf, which is due to changes in water mass stratification, affecting the convection depth in the period of cooling before ice formation.

Long-term variations of ice thickness by May 1, according to simulation data, show that differently directed processes are taking place: the simulated ice thickness tends to decrease (at a rate of up to –6 mm/year) in the Gulf of Taz and, partly, in the southern Gulf of Ob, and tends to increase (up to 4 mm/year) in the northern part of the gulf. The anthropogenic activity in the river basin has led to a small decrease in the mean ice thickness by May 1 practically all over the gulf water area, except for its northernmost part near the marine bar; the simulated decrease was largest at the western shore in the central part of the gulf—on the average, by 3 cm.

The obtained estimates were used to compile a scheme of zoning of the Gulf of Ob by the extent of the effect of external natural and anthropogenic factors in the river drainage basin on the mouth processes in the Gulf of Ob over the historical period (Fig. 9).

ESTIMATING THE FUTURE LONG-TERM VARIATIONS OF ICE–HYDROLOGICAL CHARACTERISTICS

The simulation of hydrological processes in the Gulf of Ob with input data corresponding to various climate scenarios shows possible considerable changes in the hydrological processes in the gulf.

Water level in the gulf changes in accordance with changes in river flow; the model shows its main changes to take place at the sites of inflow of rivers and to attenuate rapidly with the distance from these sites.

The range of variations of the intrusion characteristics is much wider than that simulated over the historical period (Table 3). The maximal inflow of seawater decreased on the average by 22 km for scenario RCP 4.5, and by 30 km for scenario RCP 8.5. The range of variations of the maximal seawater inflow is greater than the historic variations of this parameter by 16 km for scenario RCP 4.5 and by 22 km for scenario RCP 8.5. The variability of the simulated maximal intrusion of seawater is greater than that over the historical period by factors of 2.5 for scenario RCP 4.5 and 1.5 for scenario RCP 8.5. On the average, the maximal simulated seawater intrusion is greater by 65–77 km.

Thus, the characteristics of seawater intrusion, simulated for the conditions of different climate scenarios go beyond their natural variability. In summer, when the estuary is on the average fresher, saline water in some years can stay farther southward than its extreme position in the historical period. In winter, the position of the simulated hydraulic front lies somewhat further northward (up to 40 km) than it does at the simulation for the historical period; i.e., under the scenarios considered here, water in the estuary becomes fresher due to changes in river flow.

Simulation for different climate scenarios has shown that the changes in the occurrence dates of ice phases relative to the current state of the Gulf of Ob are mostly due to atmospheric factors and the change from the relatively warm modern period to a colder period in the future. The effect of atmospheric factors on ice phases is much more significant than the effect of changes in river flow due to climate changes in river drainage basin.

CONCLUSIONS

The simulation of flow formation on WBM model showed heterogeneous changes of the annual runoff over the drainage area of the Gulf of Ob over period 1980–2018. A tendency can be seen toward an increase in the annual runoff in the eastern part of the basin and in the lower reaches of the Ob; this tendency is in general agreement with changes in annual precipitation. The analysis of seasonal runoff and the components of its formation showed that the increase in the annual runoff is mainly due to its growth in autumn–winter, when the runoff is mostly formed with groundwater inflow. Model calculations showed that the effect of economic activity in the river basin had led to a considerable (by 20–25%) increase in winter flow of

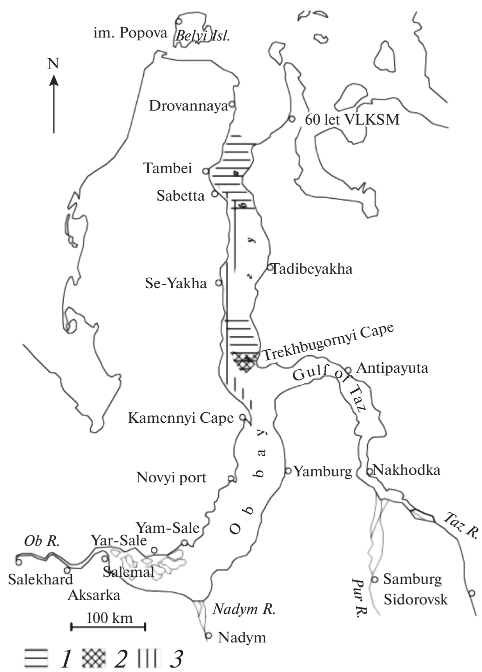

Fig. 9. Schematic map of zoning the Gulf of Ob by the influence of external natural and anthropogenic factors, in the river drainage basin on hydrological mouth processes over historical period. (*1*) Regions of annual variations of seasonal positions of the frontal zone; (*2*) the region of changes in the limiting position of the frontal zone under the effect of economic activity in the river basin, (*3*) the basin of the maximal effect of economic activity on the river basin on ice thickness.

the Ob River at Salekhard and to a minor decrease in the summer–autumn flow. Estimates of the future runoff changes by the year of 2050 based on climate scenarios RCP 4.5, RCP 8.5 showed that a considerable increase in the river inflow into the Gulf of Ob is expected, mostly due to an increase in the Ob river flow by up to 6.8%. On the other hand, the increase in the discharge of other large rivers, flowing into the Gulf of Ob, will be from 2.4% for the Pur to 8.1% for the Taz River.

The results of application of a cascade of models show that the long-term natural and anthropogenic changes in the river drainage basin by the present time have not caused considerable unidirectional changes in the hydrological fields in the Gulf of Ob.

At the same time, we can make a very important conclusion that the data of integrated hydrological surveys carried out in 1970–1980 can serve as a basis for estimating the effect of the newly constructed approach channels on the hydrological fields in the Gulf of Ob. As no integrated studies of seasonal hydrological characteristics have been carried out in the Gulf of Ob immediately before the dredging operations, the present-day conditions of the gulf can be compared with the state of the gulf before the construction of the channels with the use of data of 1970s–1980s.

The simulation of the seasonal dynamics of the hydrological fields in the Gulf of Ob with a single varying factor—river flow—have shown that, to study the limiting states of the system, it is not enough to reproduce the seasonal variations of hydrological processes within a single year with extreme flow characteristics, and the simulation of a series of years is required.

Simulations for the future showed that changes in the drainage basin leading to an increase in river flow will contribute to lesser penetration of saline water into the gulf in winter and to a greater seaward shift of the hydrological front in summer.

The proposed methodological approach with the use of observation data and multimodel experiments can be used in the future to study seasonal hydrological processes in other mouth areas, marginal seas, and the ocean as a whole and can be extended by incorporating hydrochemical and biotic processes.

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Table 3. Characteristics of seawater intrusion in the Gulf of Ob by the data of simulation over 2021–2065

Boundary conditions	RCP4.5		RCP8.5	
intrusion characteristic	maximal inflow*	maximal outflow*	maximal inflow*	maximal outflow*
Maximal, km	–266	–96	–282	20.8
Minimal, km	–164	150	–174	160
Range, km	102	246	108	139
Average, km	–221	99	–213	112

* from the beam of Tambei Settl. "–" toward the river, "+" seaward.

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