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Hydrological discharge model for the Siberian region

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Introduction

The global hydrological cycle in the atmosphere and ocean plays an important role in determination of the climatic state of the Earth. The atmosphere transfers to the continents about 40 th km^3 of fresh water per year. Directly above the continents, this volume is supplemented with an additional amount of water due to evaporation and transpiration of vegetation. After precipitation above the continents occurs, the balanced reverting flow from them into the ocean will apparently make 40 th km^3, largely composed of river run-off and a considerably lesser amount of ground water. The ocean transfers water by means of the "conveyor belt" mechanism from high and moderate latitudes to tropical zones, where they enter the atmosphere because of evaporation. The atmospheric processes transfer this water to moderate and high latitudes where it falls as precipitation onto oceans and continents, then the cycle repeats.

1. The role of Siberian rivers in the hydrological cycle and their impact on climate

The bulk of the "conveyor belt" [1] is deep convection occurring in the Labrador and the Greenland seas that forms the deep Atlantic water, the latter propagating in the deep layers in the Atlantic ocean towards South, then to the Indian and the Pacific oceans within the global water cycle. The convection is caused by carrying away the dense cold surface water from the Arctic basin as ice or surface waters of Canadian Archipelago. Making 5 % the World ocean area and 1.5 % its volume, the Arctic ocean contributes to the World ocean about 10 % volume of the whole fresh water per year [2]. This amount of fresh water is equally shared between precipitation and river run-off into the Arctic Ocean. A decrease in the fresh water flow from the Arctic basin may bring about the violation of the deep convection mode and, as a result, the violation of the global hydrological cycle. On the other hand, the arising in these periods positive anomaly of the surface temperature in the North Atlantic causes anomalous circulation in the atmosphere, the so-called North Atlantic Oscillation. This fact was established from the observations data and is the reason of climatic changes in the European regions on decades scales. The ice formation in the Arctic basin is an important part of the climatic system. An essential source of entering fresh water into the upper Arctic Ocean is the river run-off, which prepares conditions for forming ice. In this connection, the role of river run-off is an important factor affecting the processes of the fresh water cycle. The main contribution here is made by great Siberian Rivers, which are about 80 % the whole water volume as compared to the contribution of the McKenzie River [2]. The rivers Yenisei, Lena, and Ob have the greatest run-off, that is, about 603, 520, and 530 km^3 per year, respectively [9]. As total, in the second half of the XX-th century, there are observed essential changes in the outlet discharge of these rivers, both of the inter-year character and the modulations associated with changes on decades scales [3]. Apparently, this is a consequence of changes in precipitation, transferred to the Siberia territory by atmospheric processes.

Based on the above-said, it becomes possible to say that the role of Siberian rivers in forming the Earth's climatic system is fairly essential, and it is necessary to develop a hydrological climatic model for an adequate interpretation both of the regional and the global climate in the models.

2. The hydrological discharge model

The model in question is based on a conception of a linear reservoir one. It consists of linear reservoirs in the gridboxes. This means that the rate of the run-off from a box linearly depends on the inflow and is proportional to the incline in the cell and inversely proportional to the distance between the centers of gridboxes. The rate of the change of the outflow from a cell or from a cells cascade in a simple version of the Kalinin–Milyukov [4, 5] model is determined by solving a sequence of ordinary differential equations of the form

$$k\frac{dQ(t)}{dt} = I(t) - Q(t), \tag{1}$$

where k is the retention time for a cell, $I(t)$ is the inflow into a cell, Q(t) is the outflow from a cell.

For a cascade consisting of n reservoirs, one should solve a system of n equations connecting inflows and outflows from sequential reservoirs

$$\begin{aligned} &k\frac{dQ_i(t)}{dt} = I_i(t) - Q_i(t), \qquad i = 1, \ldots, n, \\ &Q_i = I_{i+1}, \quad I_1 = I(t), \quad Q_n = Q(t). \end{aligned} \tag{2}$$

The linear differential equations of the form (1), (2) in terms of the discharge $Q(t)$ can be solved in different ways: by the finite difference method [5], or as a convolution integral [4, 6]. In the latter, one can use the general solution of equation (1) for the zero initial condition convolution (Duamel's) integral between the input $I(t)$ and the system function $h(t)$ of the catchment,

$$Q(t) = \int_0^\infty I(\tau)\, h(t-\tau)\, d\tau. \tag{3}$$

For the linear reservoir, the system function can be expressed as

$$h(t) = \frac{1}{k}\, e^{-t/k}. \tag{4}$$

For the cascade of n linear reservoirs, the following expression for the system function is valid:

$$h(t) = \frac{t^{n-1}}{k^n\,(n-1)!}\, e^{-t/k}. \tag{5}$$

In a concrete realization of the model, we will use the structure proposed in the Max-Plank Institute in Hamburg [6, 10].

In the approach under consideration, a lateral waterflow is separated into three components: the overland flow, the baseflow (ground flow), and the riverflow. The retention coefficient values for the overflow and the riverflow are found from formulas depending on a gridbox incline or on a height difference between the adjacent gridboxes related to a distance between their centers.

The retention coefficient of the ground flow for a gridbox is considered to be constant.

Each elementary cell of the model has eight possible directions of a waterflow into the neighboring cells as combination of four coordinate geographical directions (N, E, S, W) and are uniquely defined from the incline of the relief.

In each cell, the content of wetlands and lakes is calculated in percentage terms [7, 8]. The effect of wetlands is parameterized by a delay factor, which has influence on the rate of the overland flow and the riverflow. The effect of the delay factor when the percent composition of wetlands in a cell is small, is negligible, however it essentially increases when a cell is filled with a large percent composition of wetlands. The effect of lakes composition is evaluated in a similar manner.

3. Results of the simulation

When carrying out numerical experiments with the use of the climatic model of the river run-off, we selected two versions of resolution, corresponding to these in the regional climatic model ECSib, which was developed in the ICM&MG SB RAS: the coarse grid resolution of 1.25×1.66° and the detailed resolution of 0.3×0.3°. The river run-off model covers the Siberian region from the Ural Mountains up to the Far East (in longitude) and from the North Kazakhstan up to the Arctic ocean (in latitude). In this model, the basins of the following rivers were taken into account: Ob–Irtysh, Pur, Angara–Yenisei, Lena, Indigirka, Kolyma, Anadyr, and Amur. The hydrological model data about the relief were corrected with allowance for uniqueness of the direction of a run-off from each cell of the grid. Cells of the overland and the ground flow were presented as individual reservoirs, while gridboxes of the riverflow were set as a cascade of reservoirs with a different number of cascades. Wetlands and lakes were accounted based on the processing of a variety of global distribution of wetlands and lakes.

For a selected version of the hydrological discharge model, it is necessary to set the following input parameters: precipitation, evaporation, transfers from a liquid to a solid phase and back, drainage into soil, and initial data. These data were taken from the calculation of the $2\times2.5^\circ$ resolution climatic model of the INM RAS (Moscow). As control data, the climatic data of the annual water flux of the Arctic Siberian rivers were employed as well as the data of the monthly averaged rivers discharge obtained in the Ob–Salekhard, Enisei–Igarka, and Lena–Kyusyur hydrological stations. The series covered the period of 1936–1990. The data for each month were averaged over the period in question, and the values obtained for each month were taken as the climatic ones.

In this paper, we discuss only the results for the Ob River catchments. The Ob River is one of the largest rivers in the Arctic. It flows North and West through the Western Siberia from the source in the Altai Mountains, emptying to the Kara Sea. The total catchments area is about 2975 th km^2, and the length about 3650 km. The Ob River contributes about 15 % of the total amount of the freshwater flow into the Arctic ocean [12]. The catchments basin is classified as follows: cropland — 36 %, forest — 30 %, wetland — 11 %, grassland — 10 % [11]. Thus, the Ob River basin is a very specific climatic area in Siberia and the analysis of the results of simulation for this area is the essential part of the hydrological discharge model validation.

Figure 1 represents the results of comparison of the calculated values including the climatic data of the yearly run-off for the Ob River. The model water flows are compared to the data from Atlas of Arctic [9] and the hydrological data. It is seen that for the model with both resolution the Ob River run-off exceeds the climatic data by 20 %, whereas the comparison with the hydrological data gives the difference 35 %.

Further it seems interesting to consider the hydrograph behavior during a climatic year as compared to the measurements data. Figure 2 represents the yearly variation of a hydrograph for the Ob River watershed. It can be seen that the model and the climatic data processed from the hydrological stations have essential differences both in amplitudes and in phases. Thus,

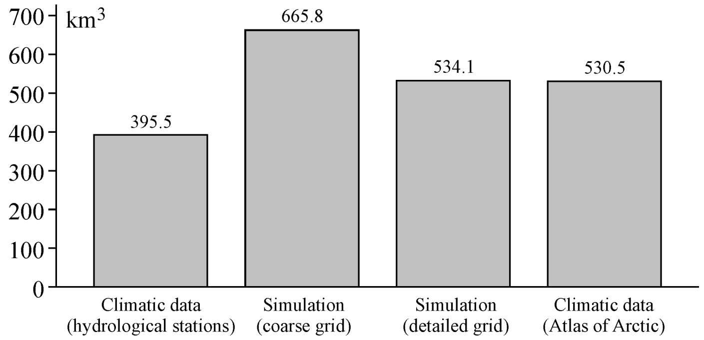

Figure 1. Comparison of Ob River yearly climatic run-off

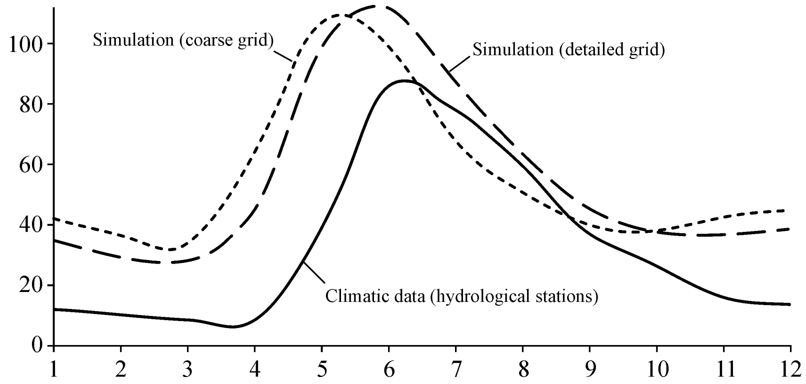

Figure 2. Comparison of Ob River inter-annual climatic run-off

the amplitude of the hydrograph for the Ob River in Salekhard zone for the coarse resolution exceeds the climatic data, and the beginning of the spring thaw flood 1–1.5 months outstrips in phase the real data. The deviations in a yearly variation of the hydrograph for the detailed grid size is a little bit closer to the Ob climatic data in phase and the amplitude of the waterflow exceeds the data by 25 % in the springtime and overheads the waterflow of the measurements data in the wintertime. These differences require further analysis of the hydrological model. Further validation of the model will be connected with the use of the NCEP/NCAR re-analysis data.

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