# River Runoff within Large River Basins of Russian Plain during Epochs of Global Warming in Past and Future

*Georgiadi A.G., Milyukova I.P., Kashutina E.A.*

*Institute of Geography, Russian Academy of Sciences, Staromonetny per., 29, 119017 Moscow, Russia*

## Abstract

**Results of an estimation of deviations of river runoff from their modern values within the largest rivers of southern slope of Russian plain observed during the period of the Late Atlantic Optimum of the Holocene (5-6 thousand years ago) and probable at global climate warming in the XXI century caused by growth of atmospheric content of greenhouse gases of an anthropogenous origin are presented. A scenarios of climatic changes results of experiments on global models of the general circulation of atmosphere and ocean, included in the international programs of comparison of results of modeling paleoclimate (Paleoclimate Modeling Intercomparison Project – PIMP) and future climate (Intergovernmental Group of Experts on Climate Change – IPCC) have been used. For estimation of hydrological changes the model of monthly water balance developed in Institute of Geography of the Russian Academy of Science (Georgiadi, Milyukova, 2000; 2002; 2006) especially for estimation of hydrological consequences of global climatic changes in large river basins which can be related to a class of macroscale hydrological is used.**

## The largest river basins of Russian Plain

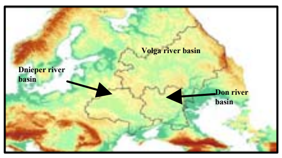



Fig. 1 Characteristics of the largest river basins of Russian Plain

| № | River basin | Outlet | Natural zones | River basin area (thou. sq. km)/ river length (thou. km) | Volume of mean annual river runoff (cub. km)/ depth of mean annual river runoff (mm) |
|---|---|---|---|---|---|
| 1 | Volga river basin | Volgograd | Forest, Forest-steppe, Steppe | 1360/3690 | 254/187 |
| 2 | Dnieper river basin | mouth | Forest, Forest-steppe, Steppe | 504/2280 | 53.5/106 |
| 3 | Don river basin | mouth | Forest, Forest-steppe, Steppe | 422/1950 | 29.5/70 |

## Model of monthly water budget

**In the model version, which is considered in this presentation, possible changes of river runoff forming on the surface and in the undersurface layer Of soil ground as well as due to drainage of deeper underground horizons of active water exchange are estimated. The initial version of the model and its subsequent modifications are stated in detail in the authors' publications [Georgiadi, Milyukova, 2002; Georgiadi, Milyukova, 2006]. The equation of water balance for river watershed for conditions of complete drainage of the zone of active water exchange of surface and underground waters can be in general put forth as follows:**

**$dW/dt = P(t) – Qs(t) – Ogr(t) – E(t)$,**

**where W water reserves in the basin for time moment t (mm); P – atmospheric precipitation, mm; Qs – sum of surface and subsurface runoff, mm; Qgr – groundwater runoff, mm; sum Qs(t) and Qgr(t) makes total river runoff (mm); E – evaporation (mm).**

**In the model the main processes of hydrological cycle are described: infiltration and accumulation of moisture in soil, evaporation (on the basis of modified Tornthwite method [Tornthwite, 1948; Willmott, Rowe, Mintz, 1985]), snow water equivalent accumulation and Snowmelt by V.D.Komarov method [Guide…,1989], formation of surface and subsurface, groundwater runoff and total river runoff. The model makes it possible to take into account macro-scale heterogeneities of hydrometeorological fields and other characteristics of territory (soils, vegetation, hydrogeology). Such approach provides the necessary degree of reliability of modeling of river runoff changes. In the modernized version of the monthly water balance model used in this work [Georgiadi, Molyukova, 2006] changes of river runoff and other elements of water balance in river basins at knots of regular grid are estimated numerically, which makes attachment with experiments data on climate models easier.**

## General scheme of calculation

**Mean monthly data on air temperature and precipitation as well as data on the field soil moisture capacity in knots of regular grid were used as the initial information for model calculations. Besides since calculations were carried with daily time spacing, monthly sums of precipitation were dispersed over days of a certain month evenly (the so-called quasi-daily data were used). Whereas for obtaining average daily air temperature values out of their average monthly values the following approach was used. It was accepted that average air temperature falls on the 15th day of each month, temperature for the 1st day of all months from January to July was accepted by Ts less, and temperature for the last day of these months was assigned by Ts more than the average monthly one. From August to December a reverse procedure was fulfilled. Within months linear interpolation between assigned air temperature for 1st 15th and the last day of each month was fulfilled. Value of air temperature deviation for the beginning and the end of a month from the average monthly (+ - Ts) was selected empirically. Calculations were fulfilled from the 1st of January to 31st of December. However for calculations besides the initial information on meteorological data and soil characteristics it is necessary to have data on moisture reserves in a meter soil layer, water reserves in snow, water reserves of ground aquifers for the date of the beginning of calculations (1st of January), and their maximum possible values. For identification of water reserves in snow for the beginning of calculations water reserves in snow for the previous three months (from October to December) were calculated by the same model, and the received value was used as the initial one for the 1st of January. As the initial values of moisture reserves in a meter soil layer while the first calculation for the 1st of October values of the least moisture capacity of soil in each point of a calculation grid were assigned. Then the initial values of moisture reserves were defined more precisely with the help of procedure of successive iterations: after each successive calculation initial and obtained in the course of calculations moisture reserves in soil for the 1st of October were compared, calculated were assigned as the initial etc. till their satisfactory convergence. Water reserves of ground aquifer for the date of the beginning of calculations and their maximum possible values were identified empirically.**

## Methods of calibration of parameters

**The model includes 10 parameters: a, a1, b, k, kf, kgr, Hgmax, Hg1, Tos, Tkp. Hgmax – the maximum water reserve of ground aquifer Hg1 – the initial (for 1st of January) reserve of ground waters, Tos – changeability of average temperature (+ - 4o), Tkp – average daily temperature of the beginning of snowmelt (from –1° up to –3°), Hgmax, Hg1, Tos, Tkp were selected empirically for each estimated region. Parameters a, a1, b, k, kf, kgr – were optimized. For identification of parameters of the model Rosenbrock procedure of optimization was used, which is a method of coordinate descent with alternative change of axes. Optimization was fulfilled simultaneously for all knots of calculation grid river basins, but the whole process of identification of parameters was divided into four stages.**

**At the first stage parameters for calculation of evaporative capacity a and a1 were optimized by average for many years data on average monthly values of evaporation at knots of grade grid for each river basins. At the second stage parameter b was optimized from relation of calculation of evaporation. At the third stage coefficient of snow melting k, coefficient of vertical filtration into ground waters kf, and coefficient of ground runoff kgr were optimized. And at the fourth stage all parameters were optimized at the same time, i.e. values got at the previous stages were put as the initial values of parameters and rather narrow limits of their changes were given. Optimization was fulfilled by the data on runoff. As practice of use of hydrological models showed such multistage procedure of identification of parameters quite justifies itself. Although usually data on runoff are the most true hydrological information, for a first approximation it may be convenient to use also some other hydrometeorological information, which usually increases reliability of identification of parameters. Thus, data from global archive prepared at the International Institute of Applied System Analysis [1999] were used as the initial values.**

## Description of the data used

### *Data on the present-day climate*

**Mean monthly values of air temperature, sums of precipitation and river runoff, soil water reserves at knots of regular grid described below were the initial information for model calculations. Besides, since calculations were fulfilled with daily spacing by time, the so-called quasi-daily data were used, i.e. monthly sums of precipitation and average temperature were interpolated for each day of the current estimated month (precipitation – evenly, temperature – evenly decreasing or increasing from the beginning to the end of a month). Mean monthly values of air temperature and precipitation at knots of regular grid of 1° x 1° from supplemented global archive prepared at the International Institute of Applied System Analysis [1999] were used. These data as well as data on river runoff and deviations of climatic elements were smoothed.**

### *Data on river runoff*

**For preparation of data on mean monthly values of river runoff at knots of regular grid of ($1^0$ x $1^0$ or less) for large river basin**

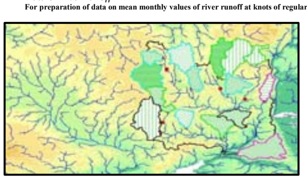


**Fig. 2. Representative sub-basins of Don river basin**

data on river runoff referred to average weighted center of basins, and then were interpolated into knots of a regular grid. In calculations data on river runoff averaged over time periods exceeding 30 years and referring mostly to time period between the 1930s-1940s and 1980s were used.

**Data on deviations of climatic elements from their present-day values**

Results obtained on the basis of numerical experiments on global climate models were used. For estimation of river runoff characteristics in conditions of Late Atlantic Optimum of Holocene, (which a number of authors consider as an analogue of future conditions corresponding to change of average global annual air temperature by $1^0$C) results of numerical experiments fulfilled on the following global models of general circulation of the atmosphere and the ocean (AOGCM) included in the PIMP program were used: MPI ECHAM3, GFDL CDG R30, UKMO HADAM2. Results of numerical experiments on models of general circulation of the atmosphere and the ocean included in the IPCC program (MPIfM ECHAM4/OPY3, HCCPR HadCM3 and GFDL-R30 were used as scenario estimations of climate changing in future.

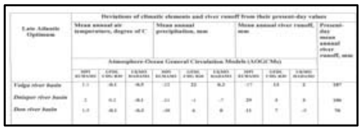
Results of model experiments proceeding from A2 and B2 families of scenarios of global socio-economic changes in XXI from the last improved SRES series of such scenarios accepted in the IPCC program were used [IPCC Special Report on Emissions Scenarios.htm, 2005]. The authors of the presentation used the two periods (2010-2039, 2040-2069) for calculation of deviations of the mean monthly sums of the atmosphere precipitation and air temperature from their present-day values (calculated for the period of 1961-1990).

## Discussion of results of simulations

**Climatic conditions**

***Late Atlantic Optimum***

**Model reconstructions of deviations of mean annual air temperature and atmosphere precipitation of this period from their present-day values obtained by MPI ECHAM3 model differ considerably from the corresponding results by another two models (GFDL CDG R30 and UKMO HADAM2). The main difference of the above-mentioned groups of reconstructions – is their distinction in the sign of deviations (Table 2). It especially concerns deviations of air temperature. According to calculations on MPI ECHAM3 model in the**



| Late Atlantic Optimum | Deviations of climatic elements and river runoff from their present-day values | | | | | | | | | Present-day mean annual river runoff, mm |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean annual air temperature, degree of C | | | Mean annual precipitation, mm | | | Mean annual river runoff, mm | | | |
| | Atmosphere-Ocean General Circulation Models (AOGCMs) | | | | | | | | | |
| | MPI ECHAM3 | GFDL CDG R30 | UKMO HADAM2 | MPI ECHAM3 | GFDL CDG R30 | UKMO HADAM2 | MPI ECHAM3 | GFDL CDG R30 | UKMO HADAM2 | |
| Volga river basin | 1.1 | -0.1 | -0.5 | -12 | 22 | 0.2 | -17 | 14 | 2 | 187 |
| Dnieper river basin | 2 | 0.2 | -0.1 | -11 | -1 | -7 | 29 | 4 | 5 | 106 |
| Don river basin | 1.3 | -0.1 | -0.2 | -10 | 6 | 8 | 11 | 7 | -3 | 70 |

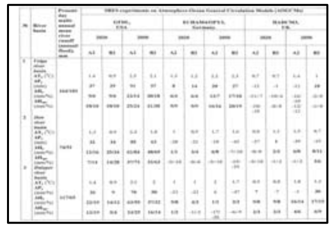
**Table 2. Deviations of climatic elements and river runoff in basins of Volga, Dnieper, and Don from their present-day values in the conditions of Late Holocene Optimum (5-6 thou. years BP).**

**period of Late Atlantic optimum basins of all rivers under consideration were characterized by warmer conditions as compared with the contemporary period. In accordance with the other two reconstructions (obtained on the basis of calculations on GFDLCDG R30 and UKMO HADAM2 models) 5-6 thousand years ago a bit colder conditions were observed on the whole territory (excluding the Dnieper river basin). Reconstructions of deviations of the atmosphere precipitation of basins of the largest rivers of Russian Plain fulfilled on MPI ECHAM3 and GFDL CDG R30 models also differ between themselves by sign, however on the average for basins they make a few per cents of the present-day values by absolute value. The first model represents a bit more humid climate, whereas the second one – more arid. According to reconstruction of precipitation obtained by the model of the Meteorological Office of UK (UKMO HADAM2 model) sign of deviations of average annual atmosphere precipitations in river basins is different, and in per cent expression value of deviations is close to zero.**

**We should note that reconstructed mean annual values of air temperature and atmosphere precipitation of Late Atlantic Optimum obtained on the basis of the model of the Max Planck Meteorological Institute, Germany, (MPI ECHAM3 model) turned to be close to the results of paleoclimatic reconstruction based on results of analysis of fossil pollen of plants [Klimanov, 1976].**

***XXI century***

**According to all three scenarios under consideration in the basins of large rivers of Russian Plain climate warming, more intensive in the middle of XXI is expected (Table 3). Situation with the geographical distribution of possible changes of the atmosphere precipitation is**



| № | River basin | Present-day multi-annual mean river runoff (annual/ flood), mm | SRES experiments on Atmosphere-Ocean General Circulation Models (AOGCMs) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | GFDL, USA | | | | ECHAM4/OPY3, Germany | | | | HadCM3, UK | | | |
| | | | 2020 | | 2050 | | 2020 | | 2050 | | 2020 | | 2050 | |
| | | | A2 | B2 | A2 | B2 | A2 | B2 | A2 | B2 | A2 | B2 | A2 | B2 |
| 1 | Volga river basin ΔTy (°C) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔPy (mm) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔHy (mm/%) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔHspr (mm/%) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 2 | Don river basin ΔTy (°C) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔPy (mm) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔHy (mm/%) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔHspr (mm/%) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| 3 | Dnieper river basin ΔTy (°C) | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔPy (mm) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔHy (mm/%) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| | ΔHspr (mm/%) | | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Table. 3. Deviations of climatic elements and river runoff in basins of Volga, Dnieper, and Don rivers from their present-day values in the conditions of anthropogenic climate warming in XXI century.**

**ΔTy (0C), ΔPy (mm), ΔHy (mm/%), ΔHspr (mm/%) – deviations of mean annual temperature, annual sum of precipitation, river runoff depth over a year and flood (March-May) correspondingly**

**more complicated. According to the scenario based on simulations on the model of the Geophysical Laboratory of Hydrodynamics of the Princeton University, the USA, it is expected that practically on the whole territory (excluding the Volga River basin lower the confluence with the Kama River) annual precipitations with increase both in the first one third of this century, and in its middle. Besides, their increase will be most evident in the middle of the century. Different situation with the atmosphere precipitation is possible in case of realization of scenarios based on calculations by the model of the Max Planck Meteorological Institute, Germany, and the Hadley Center on investigation and forecast of climate, UK. According to calculations by the first model on the average for the Volga river basin at both stages of climate warming we should expect increase of the atmosphere precipitation whereas in the Don and Dnieper rivers basins almost general but insignificant decrease of the atmosphere precipitation is possible. Forecast scenarios of the Hadley Center are characterized by different sign and absolute value of future changes for different river basins but come mainly to little decrease of precipitation.**

## Hydrological conditions

***Late Atlantic Optimum of Holocene***

**Mean annual river runoff (Table 2)**

**The most evident decrease of river runoff in Late Atlantic Optimum of Holocene (proceeding from paleoclimatic reconstruction obtained by calculations on MPI ECHAM3 model), which exceeded 10% as compared with the contemporary period, was observed in the Volga river basin, which is also close to results obtained earlier based on traditional methods of paleoreconstructions and statistical dependencies of runoff on climatic elements [Velichko et al., 1988]. At the same time according to this scenario in the basins of the Dnieper and Don rivers the greatest positive deviations of annual river runoff, which reached 27% and 16% correspondingly, were observed. Calculations of deviations of mean annual river runoff based on paleoclimatic reconstructions by the GFDL model testify to the fact, that in the Late Atlantic Optimum of Holocene in the basins of all large rivers of Russian Plain annual river runoff was higher than the present-day one, also insignificantly, excluding the Dnieper river basin and the southern part of the Volga river basin where deviations make 10% and more. Also insignificant (excluding the southern part of the Volga river basin) and different by sign values of annual river runoff from its preset-day values were obtained on the basis of paleoclimate reconstruction by results of calculations on UKMO HADFAM2 model.**

**Intra-year distribution of river runoff (Fig. 3)**

**The most evident differences of hydrological features of the two compared periods – the Late Atlantic Optimum of Holocene and the contemporary period – manifest themselves most pronouncedly in change of the character of the intra-year distribution of hydrological regime elements. Even in case of slight deviations of river runoff (see Table 2) appreciable differences in its intra-year movement are registered (Fig. 3) . Besides sensitiveness of the intra-year distribution to climate changes is most pronouncedly manifested at boundaries**

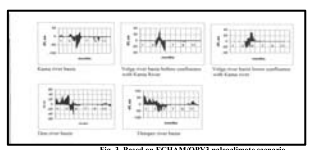


**Fig. 3. Based on ECHAM/OPY3 paleoclimate scenario**

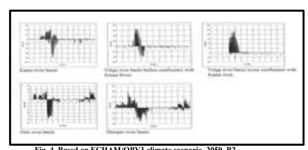


**Fig. 4. Based on ECHAM/OPY3 climate scenario, 2050, B2**

**of hydrological seasons of a year, especially winter-spring, and in the regions where contemporary winters are unstable, i.e. in more southern and western regions of Russian Plain. Just due to these reasons two types of response of the intra-year distribution of runoff in large river basins of Russian Plain are singled out. Basins of the Dnieper and Don rivers, in which much more appreciable differences are observed, which embrace not only the flood phase, but the whole winter period as well, belong to one of them (see Fig. 3). In this case in the conditions of the Late Atlantic Optimum flattening of discharge hydrograph of river runoff, and "appearance" of flood season in winter period occur. In case of the second type (The Volga river and its parts) compact transformation of flood wave by way of redistribution of runoff between two main months of flood is observed; the peak of the flood shifts to earlier time period and decreases. The singled out types of response of the intra year distribution of runoff to climate changes of such scale remain with certain variation for all the three paleoclimatic reconstructions under consideration.**

***XXI century***

**Mean annual river runoff (Table 3)**

**According to climatic scenario of the Geophysical Laboratory of Hydrodynamics of the Princeton University, the USA, in each basin the most appreciable increase both of annual runoff and flood runoff can be expected. The most significant increase can occur in the middle of the century, and especially in the basins of the Don and Dnieper rivers. Calculations based on climatic scenario of the Max Planck Meteorological Institute, Germany, show that in the basin of the Volga River increase of runoff is also possible, but less significant as compared with the one considered above. In the basin of the Don and Dnieper rivers according to this scenario, on the contrary, decrease of river runoff can be expected, which will be especially significant in the middle of the century. Calculations based on the climatic scenario of the Hadley Center on investigation and forecast of climate, UK, testify to primary decrease of river runoff in the basins of the Volga and Don rivers. At the same time under this scenario runoff in the Dnieper river basin of can a bit increase. Distribution of possible changes of river runoff over the territory of the Volga river basin is characterized by evident heterogeneity. Besides according to scenarios of the Geophysical Laboratory of Hydrodynamics of the Princeton University, the USA, and the Max Planck Meteorological Institute, Germany, almost everywhere increase of river runoff is expected, whereas basing on the scenario of the Hadley Center on investigation and forecast of climate, UK, in each part of the basin decrease of runoff can be expected. Besides the greatest variability of scenario estimations of river runoff changes both by the absolute value and sign is characteristic of the part of the Volga river basin situated lower the confluence with the Kama River.**

**Intra-year distribution of river runoff (see Fig. 4)**

**According to all climatic scenarios considered in each of the basins considerable changes of intra-year distribution of river runoff by months can occur. Considered features of change of inter-year distribution of runoff are typical both for Late Atlantic Optimum and future climate warming. Similar two types of response of the intra-year distribution of runoff in large river basins of Russian Plain during XXI are singled out. But scales of intra-annual river runoff distribution can be more significant in XXI.**

## Conclusions

***Late Atlantic Optimum of Holocene***

**In the considered model reconstructions of paleoclimate of basins of the largest rivers of Russian Plain climate conditions of the Late Atlantic Optimum of Holocene are reproduced in different ways. Reconstructed model values of deviations of the mean annual air temperature and atmosphere precipitation differ between themselves both by the absolute value and sign. The mean annual values of paleoclimate elements obtained on the basis of the model of the Max Planck Meteorological Institute, Germany, (MPI ECHAM3 model) turned to be close to the results of the paleoclimatic reconstruction based on the results of the analysis of fossil pollen of plants.**

**The most evident decrease of mean annual river runoff in the Late Atlantic Optimum of Holocene (proceeding from the paleoclimatic reconstruction obtained by calculations on MPI ECHAM3 model), which exceeded 10% as compared with the contemporary period, was observed in the basin of the Volga River, which is also close to the results obtained earlier, which are based on traditional methods of paleoreconstructionsn and statistical dependencies of runoff on climatic elements. At the same time according to this scenario in the basins of the Dnieper and Don rivers 5-6 thousand years ago considerably greater runoff, which exceeded the present-day one by 25% and 16% correspondingly, was observed.**

***XXI century***

**According to scenarios of climate change of the Geophysical Laboratory of Hydrodynamics of the Princeton University, the USA, the Max Planck Meteorological Institute, Germany, and the Hadley Center on investigation and forecast of climate, UK, in the basins of the largest rivers of Russian Plain in XXI very considerable, close between themselves and relatively even by territory increase of the mean annual air temperature is expected. At the same time trend and scales of change of the atmosphere precipitation of the territory differ considerably, but at the same time their forecasted changes do not exceed 10-15% of the present-day mean annual sums of precipitation.**

**The greatest increase of river runoff is possible in the basins of the Volga, Don, and Dnieper rivers, if the climatic scenario of the Geophysical Laboratory of Hydrodynamics of the Princeton University, the USA, is realized. In case of realization of the climatic scenarios of the Max Planck Meteorological Institute, Germany, and the Hadley Center on investigation and forecast of climate, UK, less considerable, both positive and negative changes of runoff can be observed.**

**Intra-annual distribution changes during warm climatic epochs in past and in future**

**Together with changes of annual runoff especially in the first one third, and by the middle of XXI century considerable changes of the intra-year distribution of river runoff by months can take place in each of the basins under consideration. Two types of response of the intra-year distribution of runoff in large river basins of Russian Plain are singled out. Basins of the Dnieper and Don rivers, in which its much more appreciable changes embracing not only the flood phase, but the whole winter period, can be expected, belong to one of them. In the second type case (the Volga River and its parts) compact transformation of flood wave by way of redistribution of runoff between two main months of flood can be observed; the peak of it will shift to earlier period and it will decrease.**

**Investigations were fulfilled under support of the Russian Fund of Fundamental Investigations (grant No. 05-05-64499).**

## Acknowledgements

**Authors are sincerely grateful to Dr. R. Leemans for the transferred global database on the modern climate prepared in IIASA.**