Assessment of extreme flood events in changing climate for a long-term planning of socio-economic infrastructure in the Russian Arctic.

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Abstract. Climate warming has been and is expected to continue to be more acute in the Arctic than at lower latitudes, which generates major challenges for economic activity in the region. Among others issues is the long-term planning and development of socio-economic infrastructure (dams, bridges, roads, etc.), which requires climate-based forecasts of the frequency and magnitude of extreme flood events. To estimate the cost of the infrastructure and operational risk in affected regime, a probabilistic form of long-term forecasting is preferable. In this study, a probabilistic model allowing simulation of a probability density function of hydrological variables based on a projected climatology, without modelling hydrological time series, is applied to estimate extreme flood events caused by spring snow melting in the Russian Arctic. The model is validated by cross-comparison of modelled and empirical probability dencity functions using the historical time series. The parameters of the probability density functions of spring flood runoff are assessed in a regional scale under several climate scenarios/projections for 2010–2039. For the Russian Arctic, an increase of 17–23 % in the mean values and a decrease of 5–16 % in the coefficients of variation of the spring flood flow depth of runoff are expected. Territories with substantial changes in the parameters of the probability density functions of the spring flood flow depth of runoff are defined, in these regions the engineering calculations of the extreme maximum discharges should be corrected to account for the expected climate change. The extreme maximum discharge for a bridge construction over the Nadym River is provided as an example of how the correction shold be applied.

1. Introduction

The economic importance of the Arctic is an increasingly recognized issue. Various government and commercial projects have been initiated internationally to develop the socio-economic infrastructure in the Arctic, among others for the important oil and gas fields in Mackenzie Valley (Canada), Prudhoe Bay (USA), as well as the Pechora and Yamal regions (Russia). To design hydraulic constructions, such as dams, bridges, roads and pipelines, and to estimate the costs and flood-related risks during the infrastructure's lifetime, information is needed on the threshold values of dangerous river discharges. These values are calculated from the upper-tail of probability density functions (PDFs) of the yearly maximum river runoff. The PDFs are usually constructed with three parametric distributions (e.g. Pearson Type III) using the mean value, the coefficient of variation and coefficient of skewness calculated from the observed time series with an assumption that these values do not change during the future or the planning horizon (Thomas, 1985).

Nowaday, there are two opposing views concerning the significance of the effects of climate changes to estimation of risks of hydrological detrimental events. According to Milly et al. (2008) these effects are already substantial, and should be taken into account by planers and water managers. Accordingly, the frequency and magnitude of extreme flood events based on historical data do not provide correct estimates for a future under changing climate. The opposing view doubts a climate-driven changes in the future frequency of the detrimental hydrological events, or at least calls to attention uncertainties in the estimates obtained based on the observed time series (Lins and Cohn, 2011; Montanari and Koutsoyiannis 2014; Serinaldi and Kilsby, 2015). We consider it improbable that changes in meteorological variables would remain unnoticed in runoff, which is an element of general water balance. From a practical point of view, a method capable of evaluating the regional scale assessment of detrimental hydrological events is required irrespective of debate concerning the extent of the real effects at changes in climate.

Climate models project a robust increase in precipitation over the Arctic and sub-Arctic (Collins et al., 2013; Laine et al., 2014). During October through March, precipitation in the Arctic is expected to increase by 35 % and 60 %, under medium and high greenhouse gas concentration pathways, respectively (RCP4.5 and 8.5), relative to the period 1986–2005 (IPCC, 2013). The projected precipitation increases in April through September are 15 % and 30 %, respectively. Due to climate warming and increased rainfall, annual-mean snowfall is projected to decrease over northern Europe and mid-latitude Asia, but to increase in northern Siberia, especially in winter (Krasting et al., 2013). Further, precipitation extremes are projected to increase, the climate model results being robust particularly for northern Eurasia in winter (Kharin et al., 2013; Toreti et al., 2013; Sillman et al., 2013). In Siberia these increases in precipitation will be accompanied by a decrease in the number of consecutive dry days (Sillman et al., 2013). Over northern Eurasia, the net precipitation (precipitation minus evapotranspiration) is also projected to increase during winter. The projected changes discussed above are likely with a high confidence (Collins et al., 2013), and therefore point to an urgent requirement to better evaluate the response of the other components of the Arctic freshwater system, including terrestrial hydrology (Prowse et al., 2015).

Two approaches are usually applied in the evaluation of the hydrological response. The physically-based approach is based on a combined use of regional climate model (RCM) projections and rainfall-runoff hydrological models (Fig. 1). RCMs provide projections of meteorological variables with a high temporal resolution, and these are used to drive a hydrological model that describes complex physical processes, such as infiltration, snow melting, and evapotranspiration. This allows the generation of synthetic time series of river discharges for individual watersheds (Archeimer and Lindström, 2015). The extreme flood events are then estimated from the simulated time series for a particular watershed. Successful applications of this approach on the catchment scale include numerous studies using physically-based rainfall-runoff models (Veijalainen et al., 2010; Lawrence et al., 2011). The large-scale rainfall-runoff models have also been used to assess the changes in the flood frequency under several climate projections by Lehner et al. (2006) for the European Arctic. One shortcoming of these studies is that the resulting flood frequency estimations are sensitive to the algorithms of the calculation of a pseudo-daily precipitation input from projected climatology provided by Global Circulation Models (GCMs) (Verzano 2009).

The second approach to evaluating the hydrological response to the expected climate change is stochastic (Fig. 1). The stochastic components are incorporated into a physically-based model performed by dynamic equations (Kuchment and Gelfan, 2011). The physically-based hydrological models (even with stochastic components) generate the flow time series (or runoff signal) based on the time series of meteorological variables. Thus, to estimate the extreme hydrological events (floods or droughts) with required probability of exceedance for a single catchment, one should run the physically-based hydrological model for the particular climate scenario (or the set of scenarios) and simulate the runoff signal. In the case of a hydrological model with stochastic components, the meteorological signal could be performed by Monte-Carlo simulations within a-priory defined random generators. In performing regional scale flood (or drought) frequency analysis using climate projections, the runoff signal should be simulated for a set of watersheds. It makes the calculations extremely costly computationally, especially in the case of climate ensembles.

The approach presented in this paper could be named as probabilistic (to distinguish from the stochastic modelling described above). This approach allows us to skip the simulations of the runoff signal, since only the parameters of PDF are directly simulated from the meteorological mean values (for projected periods of 20–30 years). These parameters are further used to model PDF with theoretical distribution, allowing us to evaluate the flood events with required probability of exceedance in the future (Fig. 1). Thus, it is easy to perform the regional scale assessment of the detrimental hydrological events (floods and droughts) in the future for a particular scenario or ensembles of the climate projections, and to detect the regions where the risks of damage to infrastructure are increased.

In the presented study, the yearly maximum runoff formed during spring flood is considered. The Pearson's system of distributions (Elderton et al., 1969) is used to model the PDF of multi-year peak flow and to estimate the extreme flood events with required probability of exceedance. The elements from the theory of random Markov processes are traditionally applied in engineering calculations to evaluate the probability of extreme hydrological events with required probability of exceedance (Kite, 1977; Benson, 1968; Kritsky and Menkel, 1946). The analysis of flood and drought frequency requires the hydrological time series (either observed, or simulated by physically-based model using the climate projections). These time series are used to estimate the parameters of PDF approximated with theoretical distributions. The idea to perform the direct simulation of PDF parameters (without the simulation of time series) is proposed by Kovalenko (1993), and Kovalenko et al. (2010) simplified the basic probabilistic model for applications of hydrological engineering. Viktorova and Gromova (2010) applied this approach to produce a regional-scale assessment of the future drought extremes for the European part of Russia. The main idea of the simplified method is the “quasi-stationarity” of the changing climate and hydrological regime. In this context, the quasi-stationarity is represented by the multi-year statistical moments for the periods of 20–30 years; the moments are different for the past (or reference period) and the future (or projected period). In contrast to the classical assumption used behing the engeenering applications, where the stationary regime is represented by the statistical parameters of the PDF, which are the same for past and future time periods. The climate projections are represented as the multi-year means of the meteorological values for the period of 20–30 years (Pachauri and Reisinger, 2007), also based on the quasi-stationarity assumption.

This probabilistic modelling provides a more economical way of producing probabilistic forecasts for extreme flood events under the expected climate change on a regional scale. This is because of (i) a low number of forcing and simulated variables (only statistical moments of climate and hydrological variables are needed); (ii) a low number of parameters (physical processes described integrally by a lumped hydrological model); and (iii) a relative simplicity of a regionally-oriented parameterization. Furthermore, the probabilistic model does not require large spatially distributed datasets and may be applied for regions of poor data coverage, such as the Arctic.

The aim of this study is to perform a regional-scale assessment of the future extreme flood events based on climate projections for the Russian Arctic. The novelty of the study includes two aspects. First, we present a method to assess the frequency and magnitude of extreme flood events in changing climate, adapted in this case to the Arctic territories. It could also be applied to other territories , as the regionally oriented parameterization is relatively simple. Second, the paper provides regional-scale estimations of changes in extreme flood events under the expected climate change for the Russian Arctic. The regional-scale assessment of the future extreme flood events is based on the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathway (RCP) scenarios. The territories are delineated where the frequency and magnitude of the detrimental floods are projected to change substantially. These maps include a warning for the regions where the engineering calculations of the extreme maximal discharges should be corrected to account for the climate changes. An example of the engineering calculation of maximum discharges of 1 % probability for the Nadym River is provided using the outputs of three climate models for the period 2010–2039.

2. Methods and data

The idea of the method is (i) to simulate the future parameters of PDF of the multi-year runoff using the projected mean values of precipitation and air temperature. Then, (ii) to construct the PDF with simulated parameters and a-priory defined theoretical distribution (Pearson Type III), and finally (iii) to calculate the maximal runoff from tailed values with required probability of exceedance. This idea is used to perform the regional-scale assessment of the maximal extremes for the northern territories, where these values occur during the spring floods. Within these territories a peak flow is usually formed by seasonal snow melting and represented by a spring flood depth of runoff (h, mm/(time period)), calculated as the volume of spring flood flow (m^3) from the drainage basin divided by its area (m^2). The reason, why the values of spring flood flow depth of runoff was chosen instead of the maximal discharge, is that this value allows mapping of the spatial distribution of a river's maximal flow over broad areas. Thus, the value of spring flood flow depth of runoff can be used in defining the regions for which the flood extreme maximum discharge should be corrected according to climate change. After such regions were delineated, the correction of maximal discharge with required probability of exceedance can be done using climate projections based on the historical discharge time series (for the watersheds with observations) as well as based on the mapped projected mean value, coefficients of variation and skewness of the spring flood flow depth of runoff (for the catchments without observations). In this case, the extreme river discharge (Q, m^{3}s^{-1}) with a required probability of exceedance (p) is calculated according method from (SP33-101-2003, 2004):

$$Q_p = k_0 \mu h_p \delta \delta_1 \delta_2 F / (F+b)^n \text{ , (1)}$$

where k_0 is a flood coincidence factor (wich reflects the water income to the catchment (due to melting), which affect to the shape of hydrograph), h_p is a spring flood flow depth of runoff (mm/(time period)) with probability p (0.1, 0.05, 0.01) estimated from an exceedance probability curve (or PDF), μ is a factor of inequality of the depth of runoff and maximal discharge statistics; $\delta, \delta_1, \delta_2$ are watershed fractions of lake, forest and swamp respectively, F is a watershed area (km^2), b is the additional area which adjusts the reduction of the runoff (km^2) and n is degree of a runoff reduction. The values of $\mu, \delta, \delta_1, \delta_2$, b and n may be obtained from look-up tables (SP33-101-2003, 2004) or from global datasets representing land cover (e.g. Bertholomee´ and Belward, 2005). To estimate the spring flood flow depth of runoff with required probability of exceedance (h_p), the PDF is constructed based on the mean value, the coefficient of variation and coefficient of skewness (e.g. Bulletin 17–B, 1982). These values are calculated from observed time series, but in our study we simulate them based on the projected climatology for the future time period 2010–2039.

2.1 Model

The core of the probabilistic hydrological model is a linear differential equation with stochastic components having solutions statistically equivalent to solutions of the Fokker–Planck–Kolmogorov (FPK) equation. It allows the evaluation of the probability density function of a random hydrological variable with parameters dependent on climate variables (Kovalenko, 2014, 1993). Under a quasi-stationary assumption of the expected climate change, the FPK is approximated by a system of algebraic equations to simulate statistical moments of multi-years runoff (see Annex for details) and to construct the PDFs with theoretical distributions (e.g. Pearson Type III). In our study, the following system of equations is used to model the first and second statistical moments of the spring flood depth of runoff:

$$\begin{array}{l} -\bar{c}\, m_1 + \bar{N} = 0 \\ -2\bar{c}\, m_2 + 2\bar{N}\, m_1 + G_{\tilde{N}} = 0 \end{array} , \quad (2)$$

where m_1 (mm) and m_2 (mm^2) are the first and second statistical moments of the spring flood depth of runoff for the period of 20–30 years; $\bar{c} = 1/k\tau$ is inverse of the runoff coefficient (k) times the watershed reaction delay (τ) ; $\bar{N}$ (mm) is the mean value of the annual precipitation amount for a period of 20–30 years. The parameter $G_{\tilde{N}}$ (mm^2) characterizes the variability of the annual precipitation amount.

The model (2) allows evaluating the multi-year runoff statistical moments for the projected time period basing on the climatology and multi-year runoff statistical moments for the reference (historical) period. The reference period is the time slice with (i) the observed data available and (ii) the steady climate and runoff regime. The "steady" is defined statistically, thus there are no significant trends and changes in the mean values of meteorological and hydrological characteristics. The climate and runoff regime for the projected time slice are also assumed to be steady. Thus, the model (2) operates within two steps of the steady climate and runoff regime, however they are represented by the statistically different mean values, coefficients of variation and coefficients of skewness (the assumption of quasi-stationarity).

The system of Eq. 2 was applied as follows:

- (i) to estimate the statistical moments from the observed hydrological and meteorological time series for the chosen reference period (m_{1r}, m_{2r} and $\bar{N}_r$);

- (ii) to assess the model parameters for the reference period:

$$\bar{c}_r = \bar{N}_r / m_{1\mathrm{r}} \ ,$$

$$G_{\tilde{N}r} = 2\left(\bar{c}_r m_{2\mathrm{r}} - \bar{N}_r m_{1\mathrm{r}}\right) \ , (3);$$

- (iii) to calculate the future values of two statistical moments ($m_{1\mathrm{f}}$ and $m_{2\mathrm{f}}$) from the projected mean of the annual precipitation $\left(\bar{N}_f\right)$, provided that the future parameter values ($\bar{c}_f$ and $G_{\tilde{N}f}$) are known:

$$m_{1\mathrm{f}} = \bar{N}_f / \bar{c}_f \ ,$$

$$m_{2\mathrm{f}} = \left(2\bar{N}_f m_{1\mathrm{f}} + G_{\tilde{N}f}\right) / 2\bar{c}_f \ , (4).$$

The values of the parameters $\bar{c}$ and $G_{\tilde{N}}$ can be set constant for the projected time period as proposed by Kovalenko et al. (2010) or predicted via regional regression equations (Shevnina, 2012) using the projected climatology. In this study, both methods of handling these parameters are considered.

- (iv) to obtain the future statistical values of the spring flood depth of runoff: the mean value and the coefficient of variation. The future coefficient of skewness was calculated from the given ratio of C_s/C_v which is considered to be constant for the reference and future periods. The future PDFs were constructed with Pearson Type III theoretical distributions based on these statistical values and used to estimate the spring flood flow depth of runoff with required probability of exceedance. Then, the extreme flood discharges were calculated using Eq. 1.

2.2 Validation

Rainfall-runoff models are usually validated against observed time series (Lehner et al., 2006; Arheimer and Lindström, 2015). The system of Eq. 2 allows simulating the parameters of PFD of the multi-year maximal runoff without producing time series. These predicted parameters of PDF for the future time periods are based on the parameters of PDF evaluated for the present period (the initial conditions of the model). The hypothesis of quasi-stationarity considers the present and future as two time periods corresponding to different statistically significant PDF parameter values (Kovalenko et al., 2010). To verify the model using historical data, two periods with different values of the PDF's parameters are required to perform the model validation. Thus, another procedure, namely cross-validation, was performed to evaluate the model efficiency. The cross-validation is a model evaluation method, which allows performing the model ability to reproduce the measurements. In simplest case, the dataset of the measurements (observations) is separated into two sub-sets, called the training set and the testing/control set. Then, the training set is used to evaluate the model parameters, which are further used to calculate the modelling (or nominally predicted) dataset to compare with the testing/control set using chosen measure (the statistical goodness-of-fit tests in our case).

For the period of observations, sub-periods with a statistically significant difference (shift) in the first statistical moments were selected. The shifts in the subsampled mean values (corresponding to the sub-periods) were detected according to the Student's *t*-test using the moving window approach (Ducré-Robitaille et al., 2003). We begin from setting the size of the first subsample to the chosen minimum (15 members) and calculating the value of *t*-test. The size of the second subsample is taken as the size of the total sample (*N*) minus the chosen minimum ([*N*-15] in Fig. 2) in this case. Then, the size of the first subsample was incremented by an iterator i=1, 2, 3 … until the size of the second subsample is equal to the chosen minimum. The values of *t*-test were calculated for each step and were linked to the years of the time series subdivision. Finally, the time series was divided by the year having the value of *t*-test exceeding the critical value 0.05 level of statistical significance. The Student's test critical values accounting the asymmetry and autocorrelation in hydrological time series were used (Rogdestvenskiy and Saharyuk, 1981). If several partitioning years were recognized, we gave preference to the year that divided the time series into two approximately equal sub-periods.

The first and second statistical moments of the spring flood flow depth of runoff for each sub-periods were calculated according to Bowman and Shenton (1998). The third moment was estimated from the entire time series and the constant ratio of C_s/C_v was calculated. The mean values of the annual precipitation and air temperature for each sub-period were also calculated (Table 1). The resulting dataset included pairs of the statistical moments for the spring flood depth of runoff (m_1^{I}, m_1^{II}, m_2^{I}, m_2^{II}), the mean values of air temperature $\left(\bar{T}^{I},\bar{T}^{II}\right)$ and annual precipitation $\left(\bar{N}^{I},\bar{N}^{II}\right)$.

For the cross-validation, we: (i) considered the first sub-period as the training and calculated the reference values of the model parameters; (ii) predicted nominally (“in the past”) the first and second moments for the second sub-period (which was considered as control). The same procedure was applied backwards. For the period of the nominal prediction two model versions were considered: (i) with the basic parameters setting as proposed by Kovalenko et al. (2010) and (ii) with the regional-oriented parameterization as suggested by Shevnina (2012). In our study, the parameter $G_{\tilde{N}}$ was considered to be constant for the projected time period. The mean values and the coefficients of variation were calculated with the nominally predicted statistical moments and the coefficients of skewness were estimated from the constant ratio of C_s/C_v for each time sub-period. Then, the multi-year PDFs of spring flood depth of runoff were constructed with Pearson Type III theoretical distribution using the nominally predicted statistics. The empirical probability distribution and nominally predicted PDF were compared for each sub-period and the goodness-of-fit between them was estimated using Pearson chi-squared and Kolmogorov-Smirnov one-sample tests. If the value of the test did not exceed the critical value of 0.05 level of statistical significance, it was considered to be successful in regard to the nominal prediction of the statistical moments. The model's prediction scores were estimated as a percentage of matching PDFs estimated from the whole dataset (Table 1).

An example of the cross-validation is given for the Yana River at the Verkhoyansk gauge (Fig. 2). In order to partition the spring flood depth of runoff time series into two sub-periods, the time series (Fig. 2, top) was first divided at the point S=1949 and the first *t*-test value was calculated. Then the *t*-test values were calculated step-by-step until the point E=1987 with increments of 1 year. At the point A=1965 (Fig. 2, bottom), the *t*-test value exceeds the *t*-critical value at 0.05 level of statistical significance. Thus, two periods were differentiated: the first sub-period, covering the interval 1935–1964 with m_1^{I}=41.2 (mm) and the second sub-period covering the interval 1965–2002 with m_1^{II}=52.3 (mm). The second statistical moments (m_2^{I}, m_2^{II}) of each period were also calculated. Then, the mean values of the annual precipitation amount $\left(\bar{N}^{I},\bar{N}^{II}\right)$ and the annual average air temperature $\left(\bar{T}^{I},\bar{T}^{II}\right)$ were also calculated for the two sub-periods. The reference values of the parameters

$\left(\bar{c}_r, G_{\tilde{N}r}\right)$ were estimated using m_{1r}^{I}, m_{2r}^{I} and $\bar{N}_r^I$ for the sub-period 1935–1964 (considered as training). Then, the nominally predicted or modelled m_{1f}^{II}, m_{2f}^{II} were calculated from $\bar{N}_f^{\mathrm{II}}$ for the sub-period 1965–2002 (considered as control). Finally, the nominally predicted mean value and the coefficient of variation were calculated from the simulated statistical moments and the coefficients of skewness were estimated from the ratio of C_s/C_v for each period. These values were used to construct the nominally predicted PDFs (or exceedance probability curves – Fig. 3) with a theoretical distribution of the Pearson Type III. Then, the nominally predicted PDFs and empirical PDF were compared (Fig. 3) by the goodness-of-fit tests. The same procedure was done backwards: the sub-period 1965–2002 was considered as training and the statistical moments were nominally predicted for the sub-period 1935–1964 (considered as control in this case).

The model cross-validation was performed with observations collected during the period from 1930s to 2000s. The observed data were extracted from the official edition of the Multi-Years/Year Books of the State Water Cadastre of the Russian Federation (see e.g. Kuznetsov, 1966). The spring flood depth of runoff time series at 76 gauges for medium size catchments (1,000–50,000 km^2) were used. The gauges are located on the territory of the Russian Arctic. The gauging sites are irregularly distributed over the territory with 65 % of the points located at the west part of the Arctic. The time series lengths vary from 26 to 77 years with an average of 51 years. The dataset has no gaps at the time series of 66 % of the considered gauges and for the time series of 18 % of the gauges have the missing values for more than 5 % of their length.

The sub-periods with statistically significant shift in the mean values of the spring flood depth of runoff were selected for 23 time series (Table 1), which is 30 % of the considered data. For the corresponding watersheds, the mean values of the annual precipitation amount and the average air temperature were calculated using the observations for 37 meteorological stations (approximately 2 stations per watershed) for each sub-period (Table 1). The observed time series of the annual precipitation amount and the average air temperature for the meteorological sites were obtained from Razuvaev et al. (1993), Radionov and Fetterer (2003), Bryazgin N. (2008, personal communication) and the multi-year catalogues of climatology (e.g. 1989).

For each gauge and sub-period the statistical moments were nominally predicted using Eq. 4 for two methods of the parameters settings (Table 2). Also, the statistical moments were considered to be constant during the entire observed period. In this case, the nominally predicted PDF for one sub-period was modelled using the statistical values calculated from observed data of the other sub-period (“no model” case in Table 3). The "no model" case illustrates the scenario in which climate change is not taken into account, and thus the parameters of PDF are not modified for the period of prediction. This case reflects the situation as considered in the guidelines for the engineering hydrology (Bulletin 17–B, 1982), which used only observed time series to evaluate the parameters of PDF. The percentage of the PDFs that matched successful to empirical PDFs according to Pearson chi-squared and Kolmogorov-Smirnov one-sample tests were evaluated for each version of the nominal prediction. Table 3 provides the percentage of the successful coincidences of the PDFs, which was obtained for whole available cross-validation dataset (46 pairs of the simulation and empirical PDFs).

The model using the constant parameters gives a more conforming result than the case of no model: the percentage of successfully matched PDF is over 5–10 percentage points higher (Table 3). Using the regional parameterization algorithm to calculate the parameter $\bar{c}$ gives an even more reliable result, with the values 11–22 percentage points higher in terms of successful nominally predicted PDFs. Hereinafter, we used the regional-oriented parameterization scheme to estimate the future parameters of PDFs of the spring flood flow depth of runoff using the climate change projections.

2.3 Data and method application

In performing of the long-term assessment of the extreme flood events in the Russian Arctic the following data sets were used: (i) the climatology for the reference period (Fig. 4 A, B), (ii) the mean values and the coefficients of variation of the spring flood depth of runoff for the reference period (Fig. 4 C, D), and (iii) the climatology for the projected period (Fig. 4 E, F). The reference climatology was obtained from the catalogues of climatology and the archive of the Arctic and Antarctic Research Institute for 209 meteorological stations (Radionov and Fetterer, 2003; Catalogue, 1989). The climatology was interpolated into the model grid nodes using the algorithm by Hofierka et al. (2002). The mean values and the coefficients of variation of the spring flood depth of runoff were extracted from the maps (Rogdestvenskiy, 1986; Vodogretskiy, 1986). The climatology for the projected period is provided by the climate models (Pachauri and Reisinger, 2007; Taylor et al., 2012).

In this study, the model results for two Special Report on Emissions Scenarios (SRES: A1B and B1) and two Representative Concentration Pathways (RCPs: 2.6 and 4.5) scenarios were extracted from CMIP3 and CMIP5 data sets. Results of climate models developed by the Max Planck Institute for Meteorology MPIM:ECHAM5 (Roeckner et al., 2003), the Max Planck Institute Earth System Model MPI–ESM (Giorgetta et al., 2013), the Hadley Center for Climate Prediction and Research HadCM3 (Johns et al., 2003), HadGEM2–A (Collins et al., 2008), the Geophysical Fluid Dynamics Laboratory GFDL:CM2 (Delworth et al., 2006) and by the Canadian Center for Climate Modelling Earth System Model CanESM2 (Chylek et al., 2011) were used. The GCMs used represent the climate projection close to the typical, and show that the hydrological modelling results do not vary much under the the climate forcing with the small differences. This paper presents the results of flood frequency analysis obtained for the models performed under the ensembles average scenarios and models. To obtain the climate forcing, the projected air temperature and precipitation mean values were corrected using the delta changes method (Fowler et al., 2007). To estimate the future climatology, the relative changes of the variables (in degrees for the temperature and in % for the precipitation) were first calculated based on the historical simulations and observed climatology for the reference period. Then these changes were added/multiplied to the projected climatology.

To estimate projected statistical moments of the spring flood flow depth of runoff, the corrected mean values of the annual amount of precipitation and the annual average air temperature in the nodes of corresponding climate model grids were used. For each grid node the mean values and the coefficients of variation of the spring flood depth of runoff were extracted from the maps (Rogdestvenskiy, 1986; Vodogretskiy, 1986). The maps were designed based on the observed data for the period since early 1930s till 1980 (Rogdestvenskiy, 1988) which was considered as a reference in our study. In producing these maps the observations on the catchments of medium size (from 1,000 to 50,000 km^2) located in the single climate zone were used. Thus, the features of runoff processes on the local scale (appeared on small watersheds) and global scale (revealed on huge watersheds located within several climate zones) do not considered as well as the floods due to ice jams and tides/surges. To obtain the mean and coefficient of variation from the maps the following steps were done: the scanning of paper maps, the image georeference, the data digitizing and interpolation into the grid nodes of the particular GCM.

The values of $\bar{c}$ and $G_{\tilde{N}}$ were calculated using Eq. 3 for each grid node. Then, the future first and the second statistical moments (the mean values and the coefficients of variation) of the spring flood flow depth of runoff were calculated according to Eq. 4 using projected climatology. The coefficients of skewness were estimated using the regional ration of C_s/C_v. The maximum discharge with the required probability of exceedance was calculated according to Eq. 1 using the projected PDFs of the spring flood flow depth of runoff constructed based on the projected mean value, the coefficient of variation and coefficient of skewness (see Section 3 for an example). Our study was performed for the period 2010–2039, since it is within this time interval that the existing and developing socio-economic infrastructure (bridges, oil/gas pipelines, roads and dams) will operate.

The idea of this method is to predict the future parameters of PDF using new climatology. In this case, the classical estimates of the uncertainties on the PDF tailed values (i.e the confidence intervals) can not be applied since the future runoff time series do no exist. The general uncertainties of the future PDF tailed values depend not only on the accuracy of the hydrological data, but also on the biases of the climate projections used to force the probabilistic model. The uncertainties of the projected values of the PDF parameters were evaluated based on the relative errors for the mean value and coefficient of variation suggested by Kovalenko (1993) and estimated to be about 15 % / 25 % for the mean values / the coefficients of variation. The changes in the PDF parameters are considered to be substantial if they exceed the reference values for more than these thresholds, and the regions with substantial changes in the mean values and the coefficients of variation of the spring flood flow depth were defined. These are warning regions for which the flood extreme maximum discharges should be corrected according to climate change, when used in the practical applications to designing hydraulic constructions and to estimating the risks during their operation.

3. Result and discussion

The analysis of the expected climate change in Russia and particularly over the Arctic region is provided by Govorkova et al. (2008) and Meleshko et al. (2008). These studies include the assessment for the territories of the Russian Federation as a whole, and do not provide the estimates specially within the geographical domain of the Russian Arctic, which was outlined in this study according to the hydrological principles as suggested by Ivanov and Yankina (1991) and further used by Nikanorov et al. (2007). For the period 2010–2039, the climatology averaged over the Russian Arctic is presented in Table 4 for the SRES and RCP scenarios. Generally, an increase of total precipitation over 20 mm (6 %) and warming of over 2.1 °C were predicted according to the SRES. For the RCP, the changes of climatology were more pronounced, and the precipitation mean values were expected to increase by more than 40 mm (12 %) and to be accompanied with a warming of 3.3 °C. The strongest increase (over 60 mm or 16 %) in precipitation with the highest warming (over 3.9 °C) was predicted by CaESM2 for the RCP 2.6 scenario (Table 5).

The future mean values and the coefficients of variation of the spring flood depth of runoff were assessed from the projected climatology using the method described above. For the entire territory of the Russian Arctic an increase of over 27 mm (17 %) in the mean values and a negligible decrease in the coefficients of variation were predicted according to the SRES scenarios for the period 2010–2039 (Table 4). Using scenarios of the IPCC Fifth Assessment

Report, the changes in the statistics of the spring flood flow depth of runoff were more notable: based on the RCP 2.6 scenario, an increase of over 38 mm (23 %) in the mean values and a decrease of over 0.03 (16 %) in the coefficients of variation were expected. The strongest increase (over 45 mm or 27 %) of the mean values with a lowest decrease of the coefficients of variation (over 0.06 or 17 %) was predicted by CaESM2 for the RCP 2.6 scenario.

According to all scenarios considered, the highest increase of the future mean values of spring flood depth of runoff (of 30–35 %) was expected for the Arkhangelsk Region and Komi Republic (Fig. 5b). Moderate changes in the mean values (of 10–18 %) are also predicted for Siberia (Fig. 5c and 5d) mostly according to the RCP scenarios. For the SRES scenarios, an increase of 10–18 % in the mean values was predicted for Kola Peninsula and Karelia (Fig. 5a), accompanied by a decrease of the coefficients of variation.

It is not straightforward to directly compare our results with those of other studies, because we address different flood characteristics, and only indirect comparison is possible. For the comparison we assume that for the Pearson Type III distributions, an increase in the mean values and the coefficients of variation leads to an increase of upper-tail values. Subsequently, present 100-year floods will be occur more frequently (Fig. 6). Also, a decrease in the mean values and the coefficients of variation leads to a decrease in the upper-tail values. In this case, we can expect that the events of 100-year floods decreases. We compared our results with the studies by Hirabayashi et al. (2008; 2013), Lehner et al. (2006) and Dankers and Feyen (2008) using this assumption. For the eastern part of the Arctic, an increase in the historical 100-year maximum discharges is predicted by Hirabayashi et al. (2008; 2013) under the SRES:A1B scenario for the period 2001–2030. This is in accordance with our results; we also expect an increase in the upper-tail runoff values since the mean values and coefficients of variation were estimated to enlarge in average for this region. For the north-east European Arctic we expect a significant increase in the frequency of present 100-year flood events. This is in contrast to Hirabayashi et al. (2013), which study presents the global scale estimates of the projected change in the flood frequency. The flood frequency is decreased in many regions of northern and eastern Europe according to Hirabayashi et al. (2013). The feasible reason for such disagreement is the spatial coarseness of the model used by Hirabayashi et al. (2013), which was calibrated using observations from watersheds larger than 100,000 km^2. In our study, the probabilistic model was calibrated using observations for watersheds of medium range. Lehner et al. (2006) used the WaterGAP model with climate projections derived from the HadCM3 and ECHAM4/OPYC3 GCMs. The results suggest that present 100-year flood events will occur more frequently in the north-eastern European Arctic in 2020s, which is in accordance with our results.

For Kola Peninsula and Karelia, we predicted a decrease of the mean values with slight increase of the coefficients of variation according to the SRES:A1B and SRES:B1 scenarios. Dankers and Feyen (2008) suggested a strong decrease of present 100-year floods for north-eastern Europe (i.e. Finland, northern Russia and part of the Baltic States) under the SRES:A2 and SRES:B2 scenarios, which is in general agreement with our results. A similar tendency for the predicted maximal discharges to decrease was obtained by Veijalainen et al. (2010) for the northern Finland using the physically-based model.

Fig. 7 represents the regions with substantial changes in the means and coefficients of variation of the spring flood depth of runoff. Hence, in these regions the frequency and magnitude of floods were expected to differ substantially from the historical (reference) period. The changes in the mean values and coefficient of variation were predicted relying on the outputs of the climate models of the Max Planck Institute for Meteorology: MPIM:ECHAM5 for the

SRES:B1 scenario and MPI-ESM-LR for the RCP 2.6 scenario. A substantial increase in the mean values is expected for the Arkhangelsk region, Komi Republic and Eastern Siberia (see Fig. 8 for the boundary of the regions). In these regions, the calculations of the spring flood maximum discharges should be corrected in line with the expected climate change. The example of the climate-based correction for the Nadym River watershed according to climate model outputs for the RCP 2.6 scenario is given below.

A new bridge over the Nadym River is currently in planning. The bridge height (and cost) assessments require the maximum discharge of rare occurrence (e.g. with a probability of exceedance of 1 %). The watershed of the Nadym River is located in the southern part of Western Siberia, where an increase of over 15–30 % in the mean values of the spring flood flow depth of runoff was predicted under the scenarios considered. Thus, the climate change impacted upper-tail maximum discharge may well be larger than the value estimated from the observed time series.

Hydrological observations for the Nadym River are available at the Nadym city (gauge number 11805 in the bottom panel of Fig. 8, the watershed area is 48,000 km^2). The statistics of the spring flood depth of runoff for this gauge were calculated from the observations for the period 1950–1980, which was considered as reference in this case (Table 6). The reference climatology was calculated by averaging the observations from the regular meteorological sites for the Nadym River catchment area for the same period. Then, the delta corrected projected climatology for the period 2010–2039 under the RCP 2.6 scenario was obtained from the CMIP5 dataset. The parameter $G_{\tilde{N}}$ was estimated according to the observed climatology and the parameter $\bar{c}$ was calculated based on the projected climatology accouding to Shevnina (2012). These values were used to calculate the projected first and second statistical moments (m_1 and C_v) of the spring flood flow depth of runoff. The projected coefficient of skewness was obtained from the constant ratio of C_s/C_v. The projected PDF was constructed using these values with Pearson Type III distribution. The spring flood depth of runoff with probability of exceedance 1 % ($h_{1\%}$, mm) was calculated for each climate projection (Table 6). Finally, the maximum discharge with the probability of exceedance 1 % ($Q_{1\%}$, m^{3}s^{-1}) was estimated from $h_{1\%}$ according to Eq. 1. The values of the parameters of Eq. 1 were obtained from the look-up tables (Guideline, 1984): k_0 equals to 1.0; μ equals to 1.0; $\delta, \delta_1, \delta_2$ equal to 0.84, 0.06 and 0.08 correspondingly; b equals to 1.0 (km^2) and n iequals to 0.17.

For the period 2010–2039 the maximum discharge of 1% probability of exceedance, calculated with averaging of the multi-model output, is 570 m^{3}s^{-1} larger than the discharge of the same probability of exceedance calculated from the observations. The largest increase of the maximal discharge was predicted according to the CanESM2 model (over 7% larger than the historical value). The maximal discharge of 8572 m^{3}s^{-1} changed the probability of exceedance from 1% (calculated from the observations) to 2.5 % (calculated according to the averaged climate projections).

4. Conclusions

A probabilistic model was applied in estimating the impact of climate change in the frequency and magnitude of extreme flood events in the Russian Arctic. The probabilistic model allows the calculation of the future extreme flood events with the required probability of exceedance without a need to simulate the future runoff time series. The projected meteorological mean values for the periods of 20–30 years were used to estimate the future flood runoff mean values as well as the coefficients of variation and skewness, to construct the PDFs with a Pearson Type III theoretical distribution. The projected frequency and magnitude of extreme flood events with a required probability of exceedance were then evaluated from the simulated PDFs.

In this study, to perform the model cross-validation the runoff data were extracted from the official issues of Roshydromet available by the order from State Hydrological Institute. However, in calculating multi-year time series of spring flood flow depth of runoff (and peak discharge), the global and regional runoff databases may be also used since daily discharge time series are required. The examples of the datasets are (i) the Global Runoff Data Centre, Germany; (ii) the Environmental Information System (HERTTA), Finnish Environment Institute; Vattenwebb by the Swedish Meteorological and Hydrological Institute.

For the other regions, in performing the regional scale assessments the steps are following: (i) to choose the middle size watersheds with catchment area from 1,000 to 50,000 km^2; (ii) to calculated the multi-year time series of yearly maximum runoff (discharges or spring flood flow depth of runoff) from the daily runoff time series; (iii) to select the time period without statistically significant trends in the multi-year time series (reference period); (iv) to estimate the mean values, coefficients of variation and skewness from the observed time series of yearly maximum runoff (the mean values of the precipitation amount and air temperature have also to be estimated for the selected period); (v) to evaluate the numerical values of the model parameters from Eq. (3); (vi) to assess the mean values of the precipitation amount and air temperature from climate projections for the period in the future; and (vii) toevaluate the future mean values, coefficients of variation and skewness of yearly maximum runoff with Eq. (4). To perform the model cross-validation and to develop the regional-oriented parameterization scheme, the multi-year time series of yearly maximum runoff with the periods of statistically significant shifts in the mean values and coefficient of variations are required.

The probabilistic model was further applied for a regional-scale assessment of extreme flood events for the Russian Arctic. The regional-oriented parameterization by Shevnina (2012) allows a successful prediction of 67–83 % of the PDFs (see Section 2.2). The projected mean values, the coefficients of variation and coefficients of skewness of the spring flood depth of runoff for the period 2010–2039 were estimated under the SRES:A1B, SRES:B1, RCP 2.6 and RCP 4.5 climate scenarios with outputs of three climate models. For the region studied, an increase of 17–23 % in the mean values of spring flood depth of runoff and a decrease of 5–16 % in the coefficients of variation were predicted depending on the scenarios considered. For the northwest of the Russian Arctic, an increase in the mean values and a decrease of the coefficients of variation were predicted. The regions with substantial changes in the mean values (over 15 %) and the coefficients of variation (over 25 %) were defined for 2010–2039. For the territories where the mean values and coefficients of variation increased substantially, the extreme flood events are projected to occur more frequently. For such warning regions where the risk of floods is increased, the engineering calculations of the maximum discharges with a low probability of exceedance should be corrected according to the projected climate change to reduce the potential hazard for hydraulic constructions, the oil-gas industry, transport infrastructure and the population.

The model presented in this study provides an affordable method to produce forecasts of extreme flood events (in form of PDF or as maximum discharge with a required probability of exceedance) under the projected climate change. This is possible due to low number of the simulated variables and parameter. The regionally-oriented parameterization of the model is also relatively simple and may be improved by involving a variance of precipitation, which could be obtained from the projected climatology (Meehl et al., 2011). However, due to its various simplifications, the model presented in this study does not allow an estimation of possible changes in spring flood timing or changes of intra-seasonal runoff variability for a particular watershed. On a regional scale, however, the method presented provides an explicit advantage to estimate extreme hydrological events under altered climate, especially for regions with an insufficient observational data. It could be useful for a broad-scale assessment to define the warning regions, where crucial increase/decrease of the extremal flood events are expected. When the warning regions are defined, a catchment-scale rainfall-runoff model could be applied to further distinguish details not anticipated by the method described in this study. The evaluation and inter-comparison of presented and rainfall-runoff models is of high interest.

Another weak point of the method is the use of look-up tables for physiographic parameters. In our study, to calculate the extreme discharges of the Nadym River we used look-up tables for the territory of the former Soviet Union from Guideline (1984). For other regions world-wide, these physiographic parameters may be derived from spatially distributed datasets, e.g. according to Bertholomee and Belward (2005). Also, an issue to be studied is the effect of the spatial resolution of projected climatology on the ability of the this model to estimate the frequency/magnitude of extreme floods for watersheds of different size.

The method described in this study was simplified for the use of engineering calculations, as the projected climatology for the periods of 20–30 years recommended by IPCC (Pachauri and Reisinger, 2007) assumes a quasi-stationary climate. In general, the quasi-stationarity assumption may be eliminated and a non-stationary regime could be considered. In this case, the PDF could be evaluated based on the full form of the Fokker–Planck–Kolmogorov equation (Domínguez and Rivera, 2010) with the multi-model climate ensemble approach (Tebaldi and Knutti, 2007).

5 Annex

The concept of such probabilistic modelling to perform a hydrological response to an expected climate change was proposed by Kovalenko (1993), it is presented further in the text as Kovalenko et al. (2010). This approach considers multi-year runoff time series (annual, maximal and minimal) as realizations of a discrete stochastic process presented as a Markov chain (Rogdestvenskiy, 1988). Then, a first order ordinary differential equation is used as a lump hydrological model to perform multi-year flow time series:

$$dQ/dt=-(1/k\tau)Q+\dot{X}/\tau \text{ , (A1)}$$

where Q is some runoff characteristic depending on a task (the discharge, the volume per year, the runoff depth per year, *etc.* – “model output”); $\dot{X}$ is the precipitation amount per year (“model input”); k is the runoff coefficient; τ is the time of reaction of the watershed to the incoming precipitation (here, τ =1 year, which physically means that the precipitation amount during one year generate the runoff from the watershed during one year); t is the time interval, equals to one year. Denoting $c=1/k\tau$ and $N=\dot{X}/\tau$ and adding random components ($\widetilde{c}$, $\widetilde{N}$ are performed as “white noise”) to $c=\bar{c}+\widetilde{c}$ and $N=\bar{N}+\widetilde{N}$ we obtain the stochastic differential equation:

$$dQ=[-(\bar{c}+\widetilde{c})Q+(\bar{N}+\widetilde{N})]\,dt \text{ . (A2)}$$

The random components are mutually correlated.

The solution of Eq. A2 is statistically equivalent to the solution of the Fokker-Planck-Kolmogorov equation:

$$\frac{\partial p(Q;t)}{\partial t} = -\frac{\partial}{\partial Q}\left(A(Q;t)\,p(Q;t)\right) + 0.5\frac{\partial^2}{\partial Q^2}\left(B(Q;t)\,p(Q;t)\right) \text{, (A3)}$$

where $p(Q;t)$ is the probability density function of the multi-year runoff characteristic (Q is considered now as a random value); $A(Q;t)$ and $B(Q;t)$ are the drifting and diffusion coefficients:

$$A(Q;t) = -(\bar{c} + 0.5G_{\bar{c}})Q - 0.5G_{\tilde{c}\tilde{N}} + \bar{N} \;;$$

$$B(Q;t) = G_{\bar{c}}Q^2 - 2G_{\tilde{c}\tilde{N}} + G_{\tilde{N}} \text{ , (A4)}$$

here, $G_{\tilde{c}}$ and $G_{\tilde{N}}$ are the measures of variability of c and N; $G_{\tilde{c}\tilde{N}}$ is the measure of correlation between the variability of $G_{\tilde{c}}$ and $G_{\tilde{N}}$.

In engineering hydrological applications and flood frequency analysis only three-parametric probability density functions are used (Bulletin 17–B, 1988). Then Eq. A3 may be simplified to a system of ordinary differential equations for three statistical moments m_i (i = 1, 2, 3):

$$\begin{aligned} dm_1/dt &= -\left(\bar{c} - 0.5G_{\tilde{c}}\right)m_1 - 0.5G_{\tilde{c}\tilde{N}} + \bar{N}\,; \\ dm_2/dt &= -2\left(\bar{c} - G_{\tilde{c}}\right)m_2 + 2\bar{N}m_1 - 3G_{\tilde{c}\tilde{N}}m_1 + G_{\tilde{N}}\,; \qquad \text{(A5)} \\ dm_3/dt &= -3\left(\bar{c} - 1.5G_{\tilde{c}}\right)m_3 + 3\bar{N}m_2 - 7.5G_{\tilde{c}\tilde{N}}m_2 + 3G_{\tilde{N}}m_1\,. \end{aligned}$$

This system can be used to calculate the statistics of the multi-year runoff: the mean $\bar{Q} = m_1$, the coefficient of variation $C_v = \sqrt{\left(m_2 - m_1^2\right)}/m_1$ and the coefficient of skewness $C_s = \left(m_3 - 3m_2m_1 + 2m_1^3\right)/\left(C_v^3 m_1^3\right)$. Additionally, the constant value of C_s/C_v ratio for the projected time period was used to simplify the Eq. A5, it is commonly applied in engineering hydrological applications to estimate the regional C_s. Also, the climate scenarios are distributed by IPCC as mean values of meteorological variables for the periods of 20–30 years. Thus, scenarios are presented expected for climate changes with an assumption of “quasi-stationarity” and this may also be applied for the hydrological regime. This allows further simplifications of Eq. A5: $dm_i/dt \approx 0$ and $G_{\tilde{c}}, G_{\tilde{c}\tilde{N}} = 0$ within these periods. Hence, Eq. A5 may be reduced to only two algebraic equations for m_1 and m_2:

$$\begin{aligned} &-\bar{c}\,m_1 + \bar{N} = 0 \\ &-2\bar{c}\,m_2 + 2\bar{N}m_1 + G_{\tilde{N}} = 0 \end{aligned} \;.$$

This system may be applied to estimate the multi-year hydrological statistical moments directly from climatology for each “quasi-stationary” time period (e.g. 2010–39).

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Table 1. The multi-year statistics of the spring flood depth of runoff and the climatology for the sub-periods with the statistically significant shift in the mean values of spring flood depth of runoff.

Notations: m_1 and m_2 are the first and second statistical moments of the spring flood depth of runoff; C_v is the coefficient of variation; C_s is the coefficient of skewness; $\bar{N}$ is the mean values of annual precipitation amount; $\bar{T}$ is the mean values of annual air temperature.

Gauge ID	River	Catchment area [km^2]	Period	m_1 [mm]	m_2 [mm^2]	C_v	C_s/C_v	$\bar{N}$ [mm]	$\bar{T}$ [°C]
01176	Bohapcha	13600	1934–1949	111	15401	0.50	2.5	421	–12.1
			1950–1980	141	23907	0.45	2.8	435	–12.4
01309	Seimchan	2920	1941–1956	190	40779	0.36	3.1	373	–11.5
			1957–1977	157	25842	0.22	5.1	305	–11.4
01623	Srednekan	1730	1935–1950	148	25067	0.38	4.0	426	–10.7
			1951–1980	180	36145	0.34	4.5	431	–11.1
03403	Malaya Kuonapka	2030	1943–1985	97.5	10848	0.36	0.8	255	–13.8
			1986–2002	116	14297	0.25	1.1	262	–13.1
03414	Yana	45300	1935–1964	41.1	2190	0.55	1.2	177	–14.8
			1965–2002	52.1	3456	0.48	1.4	178	–14.6
03518	Nera	2230	1944–1985	67.0	5439	0.46	0.8	227	–15.8
			1986–2002	84.6	8214	0.37	1.0	222	–14.4
09425	Turukhan	10100	1941–1970	232	56198	0.21	1.3	491	–7.4
			1971–1999	260	70304	0.20	1.4	494	–7.4
11574	Pyakupur	31400	1954–1970	142	21140	0.22	4.2	482	–6.4
			1971–2001	162	27884	0.23	3.7	514	–6.0
11805	Nadym	48000	1955–1974	162	27632	0.23	3.0	490	–6.4
			1975–1991	140	21607	0.32	2.2	471	–5.0
70047	Solza	1190	1928–1958	190	38356	0.25	0.9	525	1.3
			1959–1980	155	26046	0.29	0.8	552	1.0
70153	Yug	15200	1931–1946	126	16716	0.23	2.0	575	1.6
			1947–1980	144	22994	0.33	1.4	591	1.6
70180	Vychegda	26500	1930–1956	147	22960	0.25	0.0	491	–0.1
			1957–1980	167	29632	0.25	0.0	550	–0.5
70360	Lodma	1400	1939–1958	219	53184	0.33	1.2	533	0.7
			1959–1977	174	32650	0.28	1.4	546	0.7
70366	Kuloy	3040	1927–1958	134	20549	0.38	1.4	467	1.0
			1959–1980	110	13582	0.35	1.5	446	0.6
70410	Pechora	9620	1914–1930	302	94159	0.18	-0.4	516	–1.0
			1931–1993	276	79535	0.21	-0.3	564	–1.0
70414	Pechora	29400	1938–1956	250	65806	0.23	0.5	490	–1.0

Gauge ID	River	Catchment area [km^2]	Period	m_1 [mm]	m_2 [mm^2]	C_v	C_s/C_v	$\bar{N}$ [mm]	$\bar{T}$ [°C]
			1957–1980	278	79262	0.16	0.8	601	–1.3
70466	Usa	2750	1936–1957	385	155399	0.22	1.5	483	–4.3
			1958–1980	424	185601	0.18	1.8	558	–5.3
70509	Izhma	15000	1933–1949	189	37779	0.24	0.1	465	–0.5
			1950–1980	160	26839	0.22	0.1	534	–0.9
70522	Ukhta	4290	1934–1949	170	30706	0.25	0.9	473	–0.5
			1950–1980	144	22032	0.25	0.9	535	–0.5
70531	Pizhma	4890	1937–1964	129	18041	0.29	0.9	486	–1.7
			1965–1980	150	24264	0.28	0.9	552	–2.3
71104	Kola	3780	1928–1958	182	35539	0.27	2.6	350	0.5
			1959–1994	203	43785	0.25	2.6	459	0.1
71199	Umba	6920	1931–1958	180	34762	0.27	0.6	414	–1.1
			1959–1994	149	23942	0.28	0.6	475	–1.6
71241	Yena	1600	1934–1948	100	10625	0.25	0.7	451	0.2
			1949–1980	129	18041	0.29	0.7	557	–0.3

Table 2. The model parameters and the nominally predicted multi-year statistics of the spring flood depth of runoff for the catchments selected for the cross-validation.

Notations: $m_{1\mathrm{f}}$ and $m_{2\mathrm{f}}$ are the nominally predicted first and second statistical moments of the spring flood depth of runoff; C_v is the nominally predicted coefficient of variation; C_s is the nominally predicted coefficient of skewness; $\bar{c}$ is the inverse of the runoff coefficient times the watershed reaction delay; $G_{\tilde{N}}$ characterizes the variability of the annual precipitation amount.

Gauge ID	Lat/Lon	Period	$G_{\tilde{N}}$ [mm^2]	$\bar{c}$	$m_{1\mathrm{f}}$ [mm]	$m_{2\mathrm{f}}$ [mm^2]	$C_{v\mathrm{f}}$	$C_{s\mathrm{f}}$
01176	62°06´N / 150°37´E	1934–1949	23366	3.79	115	16234	0.48	1.20
		1950–1980	24841	3.09	136	22647	0.46	1.28
01309	63°17´N / 152°02´E	1941–1956	18370	1.96	155	28815	0.44	1.38
		1957–1977	4635	1.94	141	20941	0.25	1.26
01623	62°22´N / 152°20´E	1935–1950	18208	2.88	150	25584	0.38	1.50
		1951–1980	17936	2.39	178	35398	0.34	1.54
03403	70°11´N / 113°57´E	1943–1985	6477	2.60	101	11383	0.35	0.27
		1986–2002	3799	2.26	113	13587	0.26	0.29
03414	67°24´N / 137°15´E	1935–1964	4390	4.32	42.0	2209	0.55	0.68
		1965–2002	4347	3.36	52.7	3425	0.48	0.68
03518	64°43´N / 144°37´E	1944–1985	6436	3.39	66.0	5243	0.47	0.38
		1986–2002	5167	2.61	86.9	8543	0.36	0.36
09425	65°58´N / 84°17´E	1941–1970	10047	2.12	233	56857	0.21	0.27
		1971–1999	10275	1.90	258	69485	0.20	0.27
11574	64°56´N / 77°48´E	1954–1970	6625	3.39	151	23906	0.21	0.86
		1971–2001	10408	3.17	152	24718	0.27	0.27
11805	65°39´N / 72°42´E	1955–1974	8398	3.02	156	25636	0.24	0.72
		1975–1991	13505	3.36	146	23220	0.31	0.66
70047	64°41´N / 39°32´E	1928–1958	12469	2.76	200	42164	0.24	0.21
		1959–1980	14391	3.56	147	23753	0.30	0.23
70153	60°12´N / 47°00´E	1931–1946	7665	4.56	130	17612	0.22	0.46
		1947–1980	18536	4.10	140	21886	0.34	0.48
70180	61°52´N / 53°49´E	1930–1956	9022	3.34	165	28465	0.22	–0.01
		1957–1980	11481	3.29	149	23969	0.28	–0.01
70360	64°25´N / 41°03´E	1939–1958	25423	2.43	224	55552	0.32	0.38
		1959–1977	14897	3.14	170	31225	0.29	0.40
70366	64°59´N / 43°42´E	1927–1958	18073	3.49	128	18970	0.40	0.55
		1959–1980	12020	4.05	115	14749	0.33	0.51
70410	61°52´N / 56°57´E	1914–1930	10098	1.71	330	111916	0.16	–0.06
		1931–1993	13730	2.04	253	67121	0.23	–0.08
70414	62°57´N / 56°56´E	1938–1956	12960	1.96	307	97330	0.19	0.10
		1957–1980	8554	2.16	227	53351	0.20	0.15

Gauge ID	Lat/Lon	Period	$G_{\tilde{N}}$ [mm^2]	$\bar{c}$	$m_{1\mathrm{f}}$ [mm]	$m_{2\mathrm{f}}$ [mm^2]	$C_{v\mathrm{f}}$	$C_{s\mathrm{f}}$
70466	66°36´N / 60°52´E	1936–1957	18000	1.25	445	205006	0.19	0.29
		1958–1980	15331	1.32	367	140521	0.21	0.38
70509	63°49´N / 53°58´E	1933–1949	10124	2.46	217	49166	0.21	0.03
		1950–1980	8271	3.34	139	20651	0.25	0.03
70522	63°35´N / 53°51´E	1934–1949	10051	2.78	192	38779	0.22	0.19
		1950–1980	9630	3.72	127	17504	0.28	0.25
70531	65°17´N / 51°55´E	1937–1964	10545	3.77	147	22867	0.26	0.23
		1965–1980	12983	3.68	132	10205	0.32	0.30
71104	68°56´N / 30°55´E	1928–1958	9287	1.92	239	59383	0.21	0.13
		1959–1994	11647	2.26	155	26536	0.33	0.85
71199	66°52´N / 33°20´E	1931–1958	10865	2.30	207	45013	0.24	0.15
		1959–1994	11098	3.19	130	18606	0.32	0.24
71241	67°18´N / 32°08´E	1934–1948	5638	4.51	124	15878	0.20	0.53
		1949–1980	12086	4.32	104	1209	0.36	0.26

Table 3. The percentage of successful fits between the nominally predicted and empirical PDFs according to the goodness-of-fit tests for 0.05 level of statistical significance.

Version of the nominal prediction	Kolmogorov-Smirnov one-sample test	Pearson chi-squared test
No model	63	41
Model with parameterization by Kovalenko et al. (2010)	67	51
Model with regional-oriented parameterization by Shevnina (2012)	74	63

Table 4. The reference (1930–1980) and projected climatology (2010–2039) and statistics of the spring flood flow depth of runoff averaged for the entire territory of the Russian Arctic.

Multi-year statistical values	Reference climatology	Fourth Assessment Report (AR4)		Fifth Assessment Report (AR5)	
		SRES:A1B	SRES:B1	RCP 4.5	RCP 2.6
The annual amount of precipitation mean value ($\bar{N}$ mm)	378	400	402	424	424
The average annual air temperature mean value ($\bar{T}$ °C)	–10.3	–8.2	–8.2	–6.9	–7.2
The spring flood depth of runoff mean value (m_1 mm)	162	189	190	201	199
The coefficient of variation of the spring flood depth of runoff (C_v)	0.30	0.30	0.29	0.29	0.25

Table 5. Projected (2010–2039) climatology and statistics of the spring flood depth of runoff averaged for the entire territory of the Russian Arctic according to the results of different climate models.

Notations: $\bar{N}$ is the mean values of annual precipitation amount; $\bar{T}$ is the mean values of annual air temperature; m_1 is the mean value of the spring flood depth of runoff; C_v is the coefficient of variation of the spring flood depth of runoff.

Dataset	Scenario	GCM	$\bar{N}$, [mm]	$\bar{T}$, [°C]	m_1, [mm]	C_v
AR4	SRES:A1B	MPIM:ECHAM5	393	–8.6	184	0.30
		HadCM3	403	–7.9	191	0.30
		GFDL:CM2	404	–8.2	192	0.29
	SRES:B1	MPIM:ECHAM5	385	–8.4	182	0.30
		HadCM3	405	–8.1	191	0.30
		GFDL:CM2	415	–8.2	196	0.28
AR5	RCP4.5	MPI–ESM	421	–6.9	201	0.26
		HadGEM2–A	420	–7.0	199	0.26
		CanESM2	436	–6.7	204	0.25
	RCP2.6	MPI–ESM	415	–7.2	197	0.26
		HadGEM2–A	419	–7.9	194	0.26
		CanESM2	438	–6.4	207	0.24

Table 6. Climatology and the statistics of the extreme flood runoff for the Nadym River at the Nadym City evaluated from the observations and under the climate projection RCP 2.6 for the period 2010–2039.

Notations: $\bar{N}$ is the mean values of annual precipitation amount; $\bar{T}$ is the mean values of annual air temperature; m_1 is the mean value of the spring flood depth of runoff; C_v is the coefficient of variation of the spring flood depth of runoff, $h_{1\%}$ is the spring flood depth of runoff with exeedance of 1%, $Q_{1\%}$ is the maximal discharge with exeedance of 1%.

Multi-year values	Period of 1950–1980	Result according to GCM			
		HadGEM2-A	MPI-ESM-LR	CanESM2	Multi model
$\bar{N}$ mm	431	483	491	519	498
$\bar{T}$ °C	–5.9	–4.0	–2.9	–2.4	–3.1
m_1 mm	160	180	184	197	187
C_v	0.28	0.25	0.23	0.19	0.22
$h_{1\%}$ mm	277	297	293	297	296
$Q_{1\%}$ m^{3}s^{-1}	8572	9177	9062	9191	9144

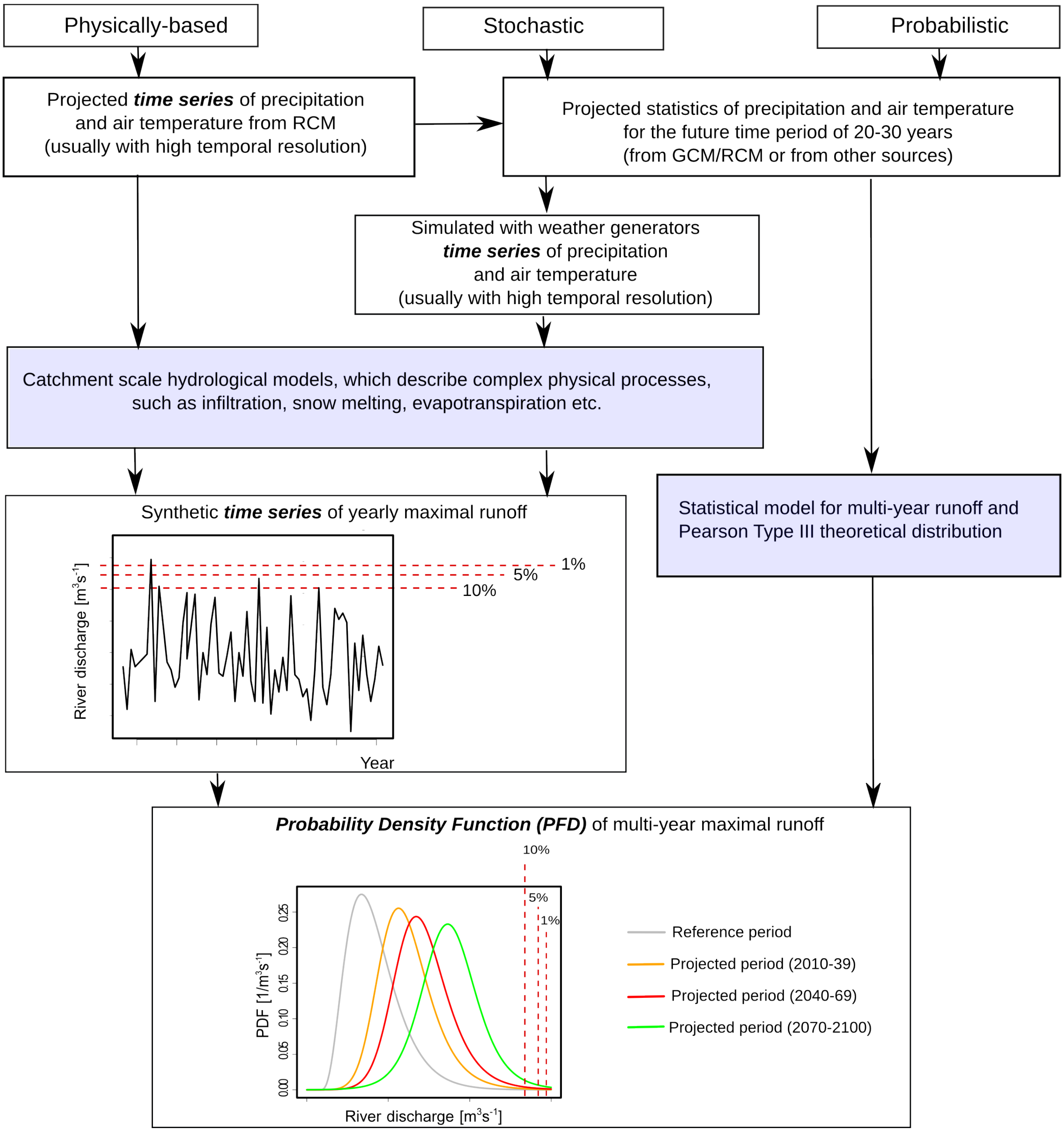

Figure 1. Three approaches to evaluate a hydrological response to the expected climate change.

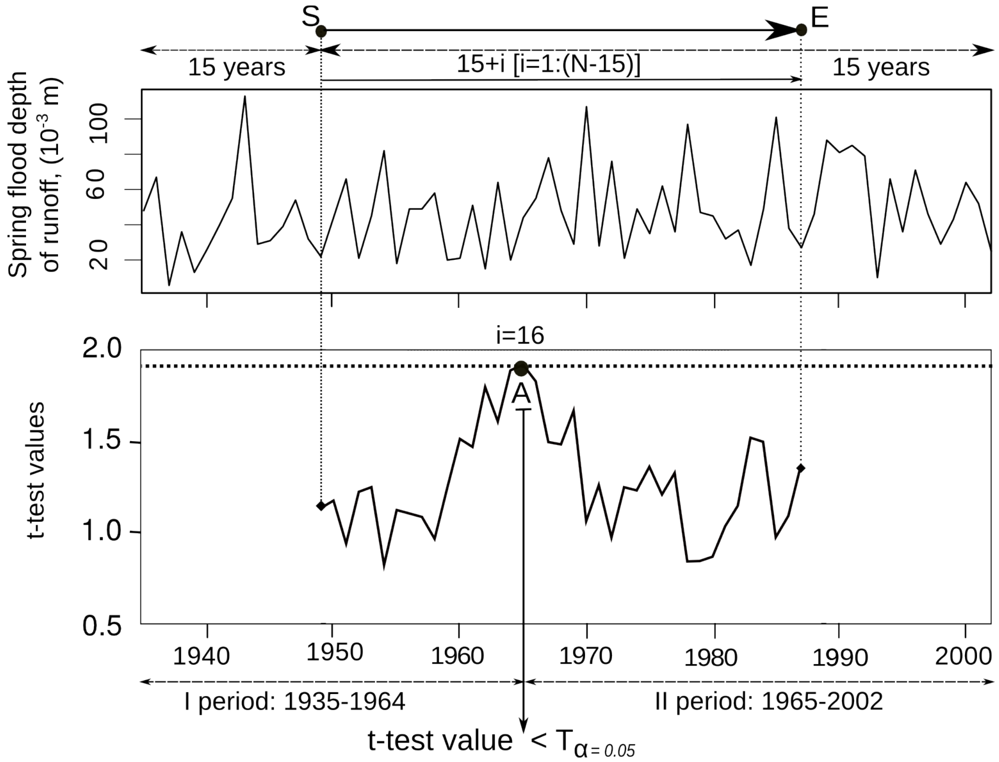

Figure 2. The partition of the observed time series of the spring flood depth of runoff (top) into sub-periods with statistically significant shift in the mean value by Student's *t*-test (bottom) for the Yana River at the Verkhoyansk City gauge: $T_{\alpha=0.05}$ is critical value of the *t*-test at the threshold of the statistical significance equal to 0.05 (dotted line on bottom).

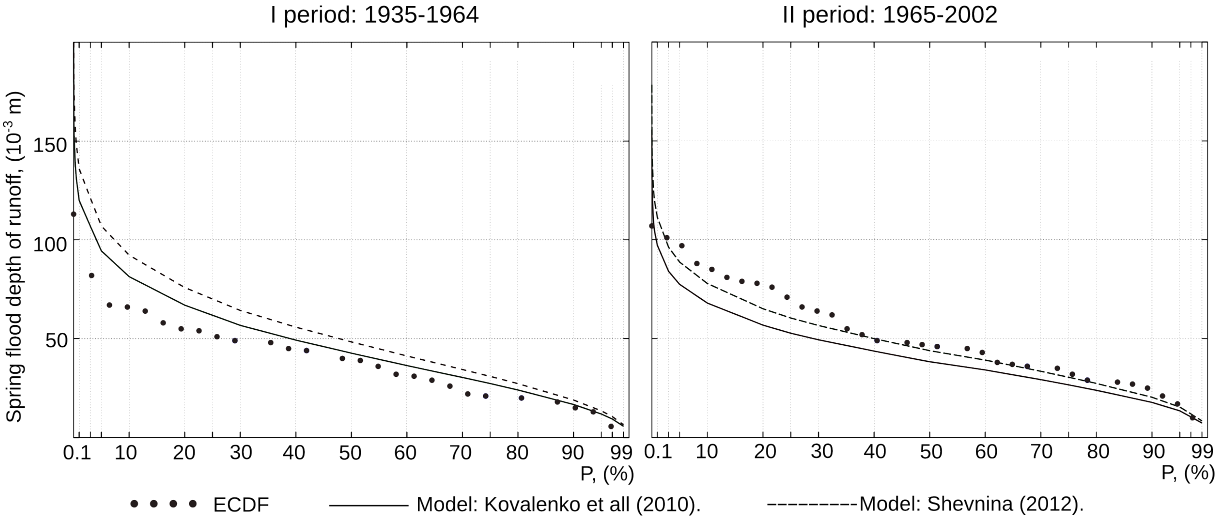

Figure 3. The nominally predicted exceedance probability curves fitted to the empirical data for the sub-periods with statistically significant shift in the mean value: the Yana River at the Verkhoyansk City (ECDF – empirical exceedance probability).

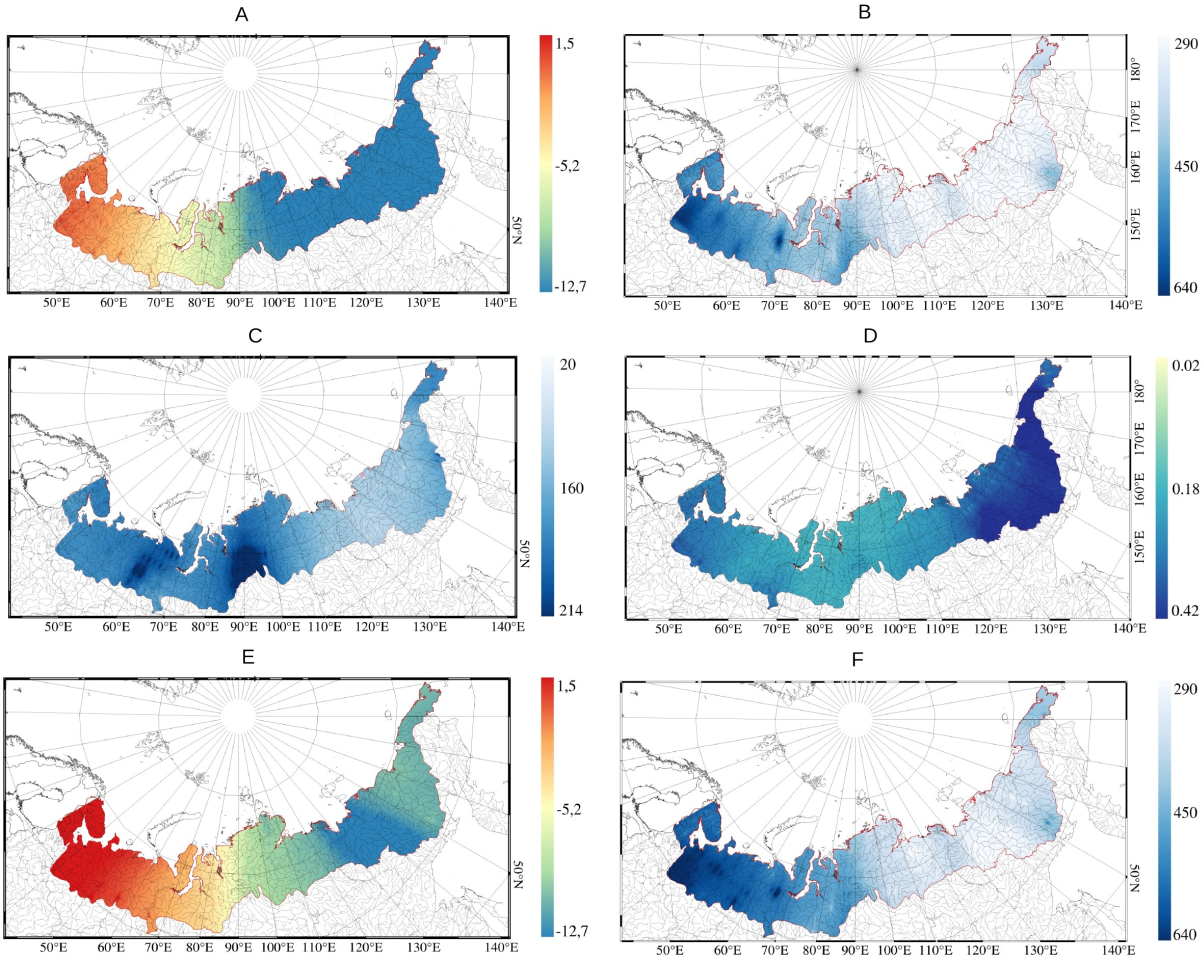

Figure 4. The datasets used in the study: A – the mean values of the annual air remperature for the reference period (Radionov and Fetterer, 2003, Catalogue of climatology, 1989); B – the mean values of the annual precipitation amount for the reference period (Radionov and Fetterer, 2003, Catalogue of climatology, 1989); C – the mean values of the spring flood flow depth of runoff for the reference period (Vodogretskiy, 1986); D – the coefficients of variation of the spring flood flow depth of runoff for the reference period (Rogdestvenskiy, 1986); E – the mean values of the annual ait temperature for the projected period (2010– 2039) under the RCP 4.5, average of four GCMs (Taylor et al., 2012); D – the mean values of the annual precipitation amount for the projected period (2010– 2039) under the RCP 4.5, average of four GCMs (Taylor et al., 2012). The territory of the Russian Arctic is outlined according to Nikanorov et al. (2007).

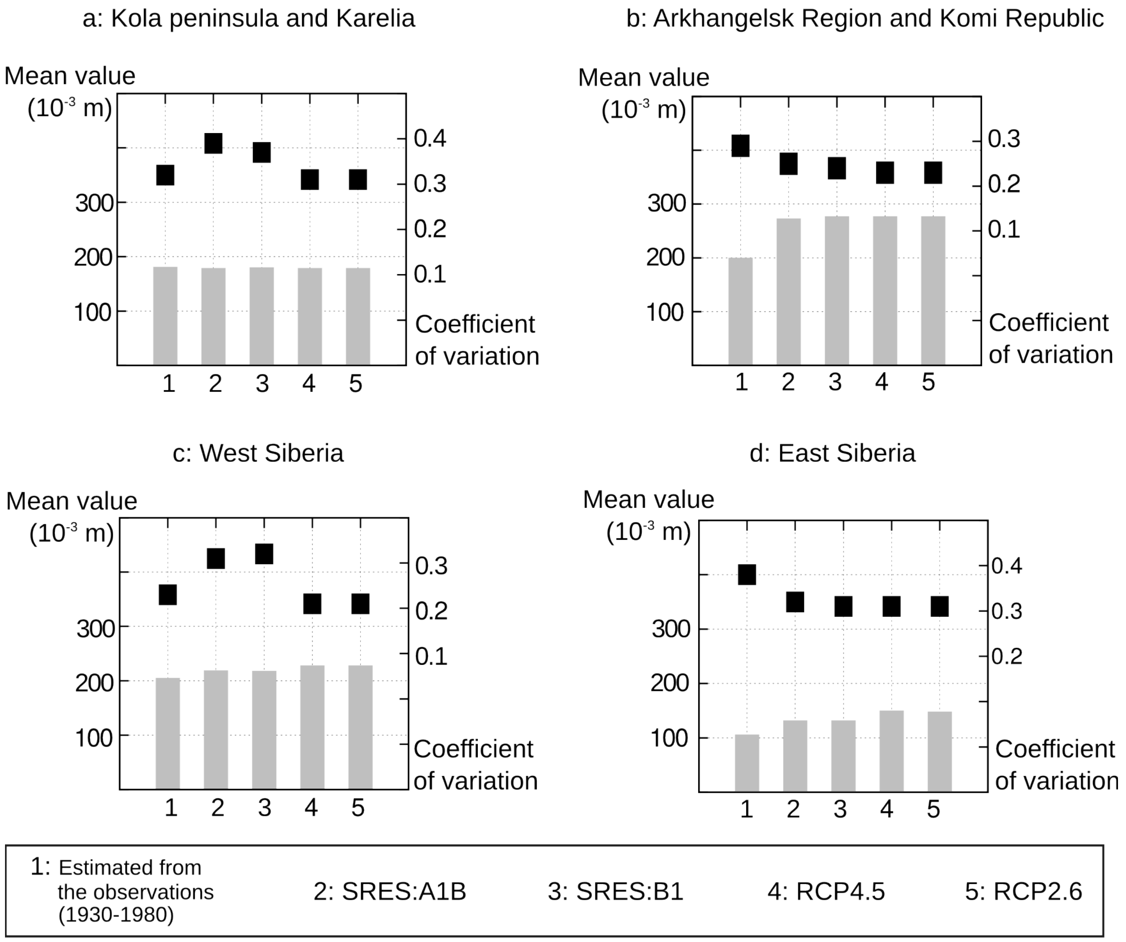

Figure 5. The changes of the mean values (bars) and coefficients of variation (squares) of the spring flood depth of runoff expected for the regions of the Russian Arctic for the period 2010–2039.

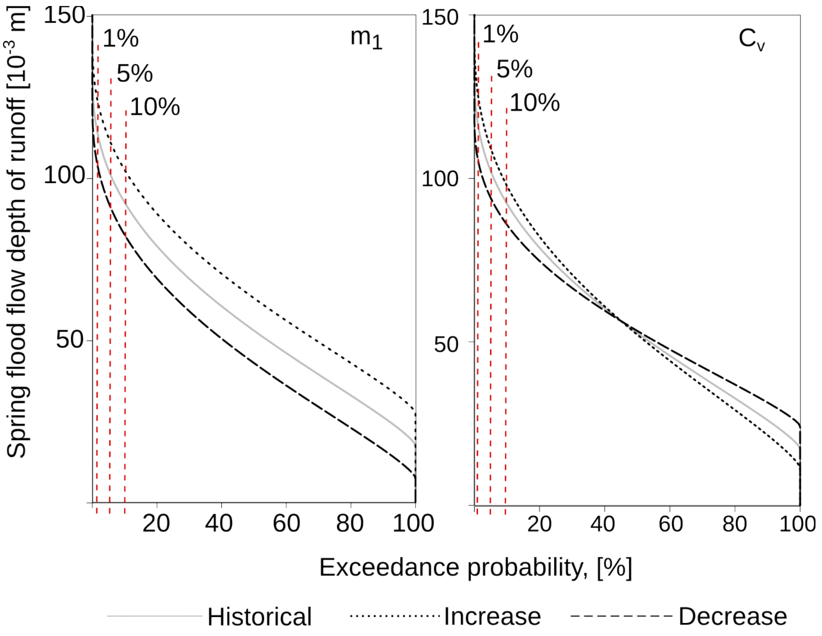

Figure 6. To illustrate the changes in the upper-tail values due to changes in the parameters of the PDF (mean values and coefficient of variation).

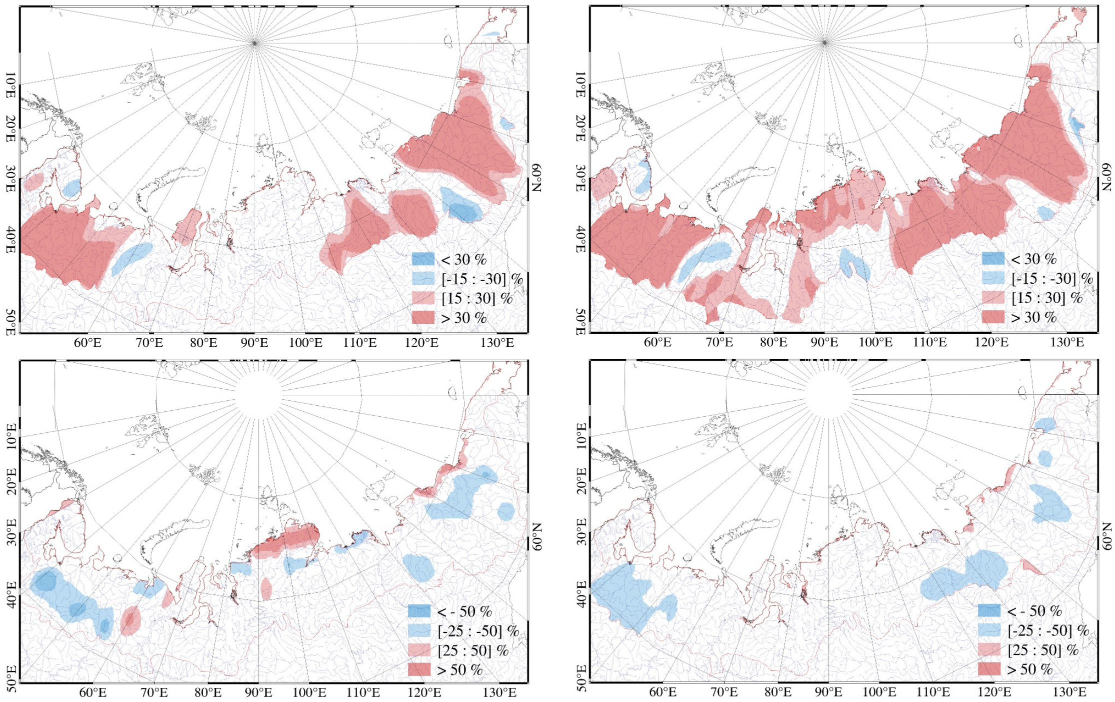

Figure 7. The regions with substantial changes in the mean values (top) and coefficients of variation (bottom) of the spring flood depth of runoff according to the MPIM:ECHAM5 under the SRES:B1 (left) scenario and the MPI-ESM-LR under the RCP 2.6(right).

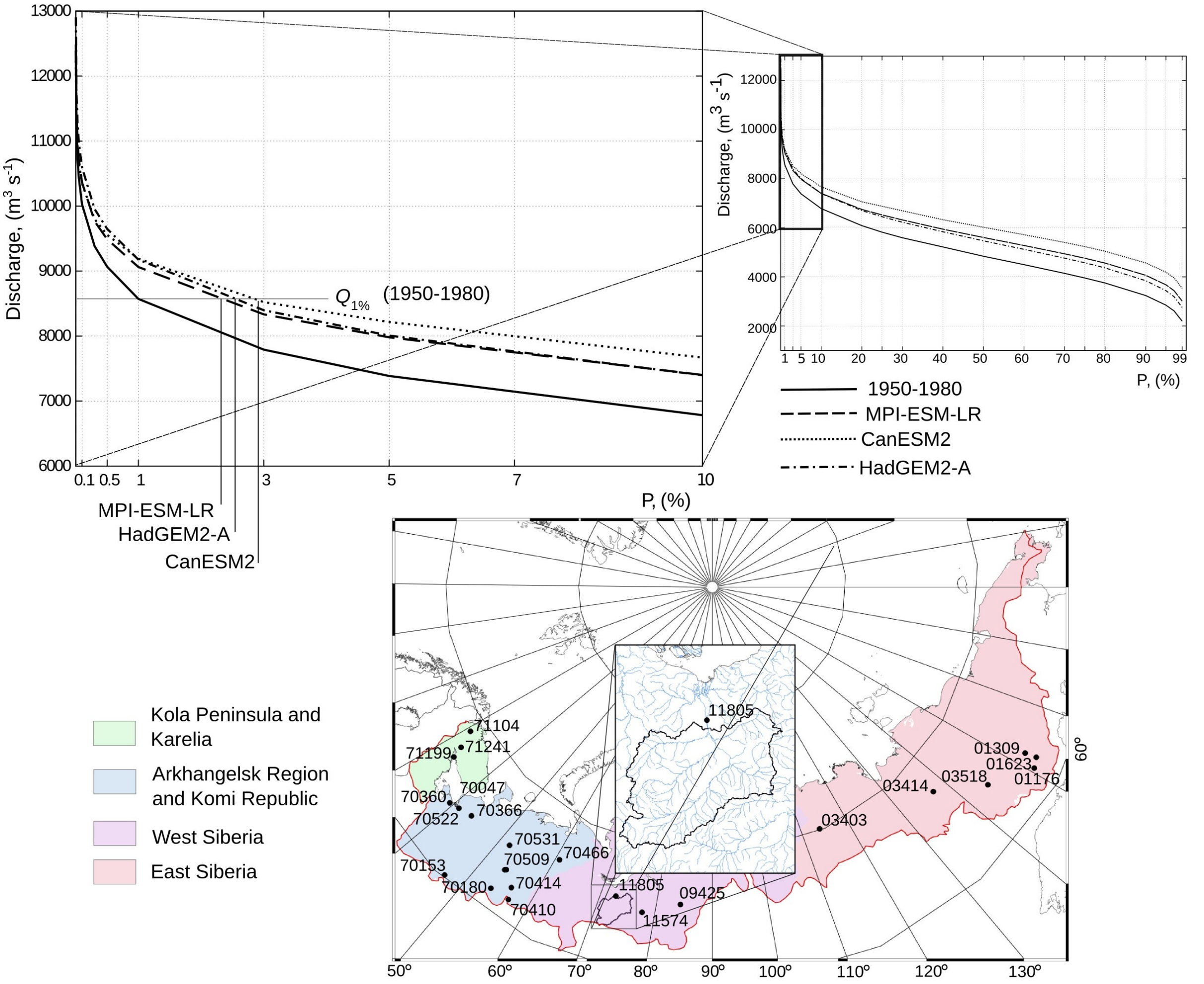

Figure 8. The exceedance probability curves of the peak-flow discharge for the period 1950–1980 and for the projected period 2010–2039 under the RCP 2.6 scenario (top) for the Nadym River at the Nadym City (11805): in the bottom figures the points and numbers correspond to the gauges used for the model (2) cross-validation.