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

Elena Shevnina[1, 2], Ekaterina Kourzeneva[1], Viktor Kovalenko[2], and Timo Vihma[1]

[1]Finnish Meteorological Institute, P.O. Box 503 FI-0010, Helsinki, Finland

[2]Russian State Hydrometeorological University, Malookhtinsky prospect 98, 195196, Saint-Petersburg, Russia

Correspondence to: Elena Shevnina (elena.shevnina@fmi.fi)

Abstract. Climate warming has been more acute in the Arctic than at lower latitudes and this tendency is expected to continue. This generates major challenges for economic activity in the region. Among other issues is the long-term planning and development of socio-economic infrastructure (dams, bridges, roads, etc.), which require climate-based forecasts of the frequency and magnitude of detrimental flood events. To estimate the cost of the infrastructure and operational risk, a probabilistic form of long-term forecasting is preferable. In this study, a probabilistic model to simulate the parameters of the probability density function (PDF) for multi-year runoff based on a projected climatology is applied to evaluate changes in extreme floods for the territory of the Russian Arctic. The model is validated by cross-comparison of the modelled and empirical PDFs using observations from 23 sites located in northern Russia. The mean values and coefficients of variation (CV) of the flood depth of runoff are evaluated under four climate scenarios, using simulations of six climate models for the period 2010–2039. Regions with substantial expected changes in the means and CVs of flood depth of runoff are outlined. For the sites located within such regions, it is suggested to account for the future climate change in calculating the maximal discharges of rare occurrence. An example of engineering calculations for maximal discharges with 1 % exceedance probability is provided for the Nadym River at Nadym City.

1. Introduction

The economic importance of the Arctic is increasingly recognized. Various governmental and commercial projects have been initiated internationally to develop the socio-economic infrastructure in the Arctic. Among others, there are projects for oil and gas fields in Mackenzie Valley, Canada (Mackenzie, 2017), in Prudhoe Bay, USA (Petrowiki, 2017), as well as in the Pechora and Yamal regions, Russia (Gazprom, 2017). To design hydraulic constructions, such as dams, bridges, roads, and pipelines, and to estimate the costs and risks of flood damage during the infrastructure's lifetime, information is needed on dangerous river discharges. These values are calculated from the upper-tails of probability density functions (PDFs) for the maximal river runoff. The PDFs are usually constructed with three parametric distributions (e.g. Pearson type III or Log Pearson type III) using the mean value, the coefficient of variation, and coefficient of skewness (SP33–101–2003, 2004; Bulletin 17–B, 1988). These parameters are calculated from observations with an assumption of stationarity in the climate and hydrological

regimes (Thomas, 1985). It means that the values of the PDF parameters and runoff extremes do not change in the future or during the period of building construction.

35   A great number of weather anomalies and detrimental flood events have been observed during the last decade. Climate change has especially been recorded in the polar regions. Climate models predict a robust increase in precipitation over the Arctic and sub-Arctic (Collins et al., 2013; Laine et al., 2014). From October to March, precipitation in the Arctic is expected to increase by 35 % and 60 %, under medium and high greenhouse gas (GHG) concentration pathways, respectively (RCP4.5 and 8.5), relative to the period 1986–2005 (IPCC, 2013). The

40   projected precipitation increases from April to September under the same GHG pathways 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, and 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

45   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 need to better evaluate the response of other components of the Arctic freshwater system, including terrestrial hydrology (Prowse et al., 2015).

50   There are two opposing opinions about climate change effects on the hydrological regime, in answer to the question: 'Is it necessary for managers and stakeholders to take account of climate change?' According to Milly et al. (2008) climate change effects are already substantial, and should be taken into account by planners and water managers. The opposing view doubts on climate-driven changes and calls attention to the uncertainties due to the short observed timeseries (Lins and Cohn, 2011; Montanari and Koutsoyiannis 2014; Serinaldi and Kilsby,

55   2015). We propose accounting for the future climate change effects on environmental risks even in the event that uncertainties can not be fully evaluated or are unknown. It is better to prevent disasters than to deal with their consequences, which may be more expensive than the initial investment. We consider that the changes in meteorological variables would remain noticeable in runoff, which is an element of general water balance. From a practical point of view, methods to evaluate the extreme flood events are required irrespective of the debates

60   about the extent or reality of the climate change (Madsen et al., 2013).
In flood estimation two main approaches are usually applied. The deterministic approach is based on the combined use of a regional climate model (RCM) and a physically-based rainfall-runoff hydrological model (Fig. 1). RCMs provide the future meteorological forcing variables with a high temporal resolution to drive a hydrological model that describes complex physical processes, such as infiltration, snow melting, and

65   evapotranspiration. This allows for generating synthetic timeseries for river runoff (discharges) for individual watersheds, so that flood events with the required exceedance probability are then estimated from the simulated timeseries. Successful applications of this approach have been achieved in numerous studies (Veijalainen et al., 2010; Lawrence et al., 2011; Archeimer and Lindström, 2015). The large-scale rainfall-runoff models have also been used to assess changes in the future flood frequency by Lehner et al. (2006) for the European Arctic. The

70   shortcoming of these studies is that the results are sensitive to algorithms calculating a pseudo-daily precipitation input from projected climatology provided by Global Circulation Models (Verzano 2009). The second approach

to evaluating the hydrological response to the expected climate change is stochastic. Weather generators are used to simulate timeseries of meteorological forcing for the physically-based hydrological model (Kuchment and Gelfan, 2011). Thus, estimates of extreme hydrological events (floods or droughts) with the required exceedance probability are obtained for a climate scenario by producing the meteorological signal by Monte-Carlo method. Both approaches are usually applied for a single catchment. In regional scale analysis, the runoff 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 probabilistic (to distinguish from the stochastic modelling described above). This approach allows us to skip the generation of the runoff timeseries, since only PDF parameters are directly calculated from the meteorological statistics for the projected periods of 20–30 years (Fig. 1). These simulated PDF parameters are further used to evaluate the future runoff values with the required exceedance probability using theoretical distributions from the Pearson system (Elderton et al., 1969). Since the probabilistic model simulates only three to four PDF parameters, this approach allows a regional-scale assessment of detrimental hydrological events in the future to be easily performed, and to define the regions where the risks of damage for infrastructure increase.

The probabilistic approach used in this study combines statistical methods with elements of the theory of Markov processes. Both have been traditionally applied in hydrological engineering calculations to evaluate design floods (Kite, 1977; Benson, 1968; Kritsky and Menkel, 1946). The traditional frequency analysis of flood and drought requires the hydrological timeseries to estimate the PDF parameters and to calculate the runoff of the required exceedance probability. However, the PDF parameters can also be estimated from the meteorological variable statistics. The idea of performing the direct simulation of the PDF parameters from the climate projections (without the simulation of timeseries) is proposed by Kovalenko (1993). Kovalenko et al. (2010) simplified the basic probabilistic model for engineering hydrology, and 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 for periods of 20–30 years. This idea allows us to represent the multi-year runoff statistically with a set of PDF parameters for the particular time window; the set is different for the past (or reference period) and the future (or projected period) climatology. Thus, climate change could be accounted for in the calculations of the runoff tailed values, which are usually required for the assessment of risks in water management. The IPCC recommends climate projections are represented as multi-year means of the meteorological values for a period of 20–30 years (Pachauri and Reisinger, 2007), i.e. under the same quasi-stationarity assumption.

The probabilistic model provides a more economical way to produce the hydrological projections for the extremes on a regional scale. This is because of (i) a low number of forcing and simulated variables (only three to four statistics for climate and hydrological variables are needed); (ii) a low number of parameters (physical processes are described integrally by a lumped hydrological model); and (iii) relative simplicity in the regionally oriented parameterization. Furthermore, the probabilistic model does not require large spatially distributed datasets and may be applied to regions with poor data coverage, such as the Arctic.

The aim of this study is to perform a regional-scale assessment of the future extreme floods based on climate projections for the Russian Arctic. The novelty of the study includes two aspects. First, we present the method to assess the frequency and magnitude of extreme floods in a 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 the projected changes in the mean values and CVs of the flood depth of runoff under four climate scenarios for the Russian Arctic. The regional-scale assessments are based on the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathway (RCP) scenarios. The regions are delineated, where the frequency and magnitude of floods are expected to change substantially. Maps include a warning for those regions where engineering calculations on extreme maximal discharges should be corrected to account for climate change. An example of the engineering calculation of a maximal discharge of 1 % exceedance probability for the Nadym River at Nadym City is provided using the outputs of three climate models for the period 2010–2039.

2. Methods and data

The idea of the method used in this study is to simulate the future PDF parameters of the multi-year peak runoff using the projected mean values for precipitation and air temperature. Then, to construct the PDF with simulated parameters and a previously defined theoretical distribution (Pearson Type III), and finally to calculate the maximal runoff with the required exceedance probability. This idea was used to perform the regional-scale assessment of the maximal runoff for the northern territories of Russia, where the peaks occur during the spring. On these territories, the peak runoff is usually formed by seasonal snow melting and may be expressed as the spring flood depth of runoff (h, mm/ (time period)), which is the volume of spring flood runoff (m^3) from a drainage basin divided by its area (m^2). The spring flood depth of runoff was chosen instead of the maximal discharge because this allows for mapping the spatial distribution of maximal runoff. Thus, the spring flood depth of runoff can be used to define regions for which the design maximal discharges should be corrected according to climate change scenarios. After such regions were delineated, the correction of the maximal discharge with the required probability of exceedance can be done using climate projections. From the spring flood depth of runoff, the river discharge with a required exceedance probability (Q_p, $m^3 s^{-1}$) is calculated according to the method proposed in SP33–101–2003 (2004):

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

where k_0 is the flood coincidence factor, which reflects a simultaneousness of precipitation/melting water input, i.e. depends on the shape of the hydrograph; μ is the factor of inequality of the depth of runoff and maximal discharge statistics; h_p is the spring flood depth of runoff (mm/(time period)) with chosen probability p (0.1, 0.05, 0.01) estimated from the exceedance probability curve (or PDF); $\delta, \delta_1, \delta_2$ are the watershed fractions for lake, forest and swamp respectively; F is the watershed area (km^2); b is the additional area that adjusts for the reduction of runoff (km^2) and n is the degree of runoff reduction. For the ungauged basin the value k_0 is estimated from observations on a neighbouring gauge located on the same type of landscape (SP33–101–2003, 2004). In our study, the value k_0 was considered to be constant for the reference and projected periods. 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. Bartholomé and Belward, 2005).

2.1 Model

The core of the probabilistic hydrological model is a linear differential equation with stochastic components having solutions statistically equivalent to the solutions of the Fokker-Planck-Kolmogorov (FPK) equation (Pugachev et al., 1974). It allows the evaluation of the probability density function of a random hydrological variable with parameters dependent on climate variables. Under a quasi-stationary assumption of climate change, the FPK is approximated by a system of algebraic equations to simulate initial statistical moments of multi-year runoff (Kovalenko, 1993, 2014) (see Annex for details). These moments are further used to calculate the PDF parameters and to model them using the theoretical formulations (e.g. Pearson Type III). In our study, the simple model suggested in Kovalenko et al. (2010) was used to model the statistical moments of the flood depth of runoff:

$$-\bar{c}\,m_1 + \bar{N} = 0$$
$$-2\,\bar{c}\,m_2 + 2\,\bar{N}\,m_1 + G_{\widetilde{N}} = 0 \quad , (2)$$

where m_1 (mm) and m_2 (mm^2) are the first and second initial statistical moments of the flood depth of runoff for a period of 20–30 years; $\bar{c} = 1/k\tau$ is the inverse of the runoff coefficient k (which is a dimensionless coefficient, the ratio of the amount of runoff to the amount of precipitation received) times the watershed reaction delay (τ); $\bar{N}$ (mm) is the mean value of annual precipitation for a period of 20–30 years. The parameter $G_{\widetilde{N}}$ (mm^2) reflects the variance in annual precipitation.

The system of Eq. (2) allows for evaluating the multi-year runoff statistical moments for the projected time period based on the climatology and multi-year runoff statistics for the reference (historical) period. The climate and runoff regime are steady within both the reference and projected periods (the assumption of quasi-stationarity). The 'steady' aspect is defined statistically, i.e. there are no significant trends and changes in the mean values of the meteorological and hydrological characteristics within the periods. However, the basic statistics (mean, CV and CS values) are significantly different for the reference and projected periods.

The system of Eq. (2) was applied as follows:

− (i) the initial statistical moments from the observed hydrological and meteorological timeseries for the chosen reference (r) period (m_{1r}, m_{2r} and $\bar{N}_r$) were estimated;

− (ii) the model parameters for the reference period were assessed:

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

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

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

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

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

The values of the parameters $\bar{c}$ and $G_{\widetilde{N}}$ were set either as constant for the projected time period (as proposed by Kovalenko et al. 2010), or dependent on the future climatology. To evaluate the projected values of the parameter $\bar{c}$ depending on the average precipitation and air temperature, the linear equations as suggested by Shevnina (2012) were

180   used. In our study, the parameter $G_{\widetilde{N}}$ was considered to be constant for the projected time period.

    – (iv) the future mean value and CV were obtained. The future CS was calculated from the given ratio of CS/CV, which was considered to be constant for the reference and future periods. The future PDFs were constructed (with Pearson type III theoretical distribution) and used to estimate the spring flood flow depth of runoff with the required exceedance probability. Then, the peak discharges were calculated using Eq. (1).

185   **2.2 Validation**

Rainfall-runoff models are usually validated against observed timeseries (Lehner et al., 2006; Arheimer and Lindström, 2015). The system of Eq. (2) allows for simulating the PDF parameters for the multi-year runoff without producing timeseries. The predicted PDF parameters for the single time-period are based on the PDF parameters calculated for the other period. Two time periods should have different parameter values and the

190   difference should be statistically significant (Kovalenko et al., 2010). Such kinds of periods were found in the observed timeseries, enabling us to perform the probabilistic model validation using a cross-validation procedure. In the simplest cross-validation procedure, the observational dataset is separated into two sub-sets, called the training set and the testing/control set. From the training set the model parameters are evaluated and then used to predict nominally the parameters of the control PDFs (Kovalenko, 1993). In our case, the nominally

195   predicted PDF was compared with the empirical distribution for the testing/control period using the Pearson chi-squared and Kolmogorov-Smirnov one-sample tests.

The whole period of observations was divided into the sub-periods with the statistically significant difference (shift) in the mean values. Dividing into the subsamples was done 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

200   the chosen minimum (15 members). The size of the second subsample in this case is the size of the total sample (N) minus the chosen minimum ([N-15] in Fig. 2). Between these two subsamples we calculate the value of the t-test. Then, the size of the first subsample was incremented by the 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 timeseries subdivision. Finally, the whole timeseries was divided by the year with the t-test exceeding the critical

205   value of p<0.05 level of statistical significance. The Student's test critical values accounting the asymmetry and autocorrelation in hydrological timeseries were used (Rogdestvenskiy and Saharyuk, 1981). If several partitioning years were found, we gave preference to the year that divided the timeseries into two approximately equal sub-periods.

The initial first and second statistical moments of the flood depth of runoff for each sub-period were calculated

210   according to Bowman and Shenton (1998). The third moment was estimated from the entire timeseries, and the ratio of CS/CV was calculated. Then, the mean values of the annual precipitation and air temperature for each sub-period were also calculated. The resulting dataset included pairs of statistical moments for the 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 a control). The same procedure was applied backwards. We validated two versions of the model: (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). The empirical and nominally predicted PDFs were compared for each sub-period and the goodness-of-fit between them was estimated using the Pearson chi-squared and Kolmogorov-Smirnov one-sample tests. If the value of the test did not exceed the critical value of p<0.05 level of statistical significance, nominally the prediction of PDF was considered to be successful. The model prediction scores were obtained as a percentage of the matching PDFs for the whole dataset.

The model cross-validation was performed with observations collected during the period from the 1930s to the 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 timeseries at 76 gauges for medium size catchments (1000–50 000 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 in the west part of the Arctic. The timeseries lengths vary from 26 to 77 years with an average of 51 years. The dataset has no gaps in the timeseries of 66 % of the considered gauges. The timeseries for 18 % of the gauges have missing values for more than 5 % of their length.

The example of the cross-validation for the Yana River at Verkhoyansk City gauge is shown in Fig. 2. In partitioning the timeseries into two sub-periods, the timeseries (Fig. 2, top) was first divided at the point S=1949 and the *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 exceeds the critical value at p<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 calculated as well. Then, the average values of the annual precipitation $\left(\bar{N}^{I}, \bar{N}^{II}\right)$ and the annual mean air temperature $\left(\bar{T}^{I}, \bar{T}^{II}\right)$ were also calculated for the two sub-periods. The reference values for the parameters $\left(\bar{c}_r, G_{\tilde{N}r}\right)$ were estimated using $m_{1\,r}^{I}$, $m_{2\,r}^{I}$ and $\bar{N}_r^{I}$ for the sub-period 1935–1964 (considered as the training). Then, the nominally predicted or modeled $m_{1\,f}^{II}$, $m_{2\,f}^{II}$ were calculated from $\bar{N}_f^{II}$ for the sub-period 1965–2002 (considered as the control). Finally, the nominally predicted mean value and CV were calculated from the simulated runoff statistics and CS was estimated from the ratio of CS/CV for each period. These values were used to nominally predict PDF (or the exceedance probability curve – Fig. 3) with the Pearson type III distribution. Then, the nominally predicted and empirical PDF were compared (Fig. 3). The same procedure was then done backwards: the sub-period 1965–2002 was considered as the training and the statistical moments were nominally predicted for the sub-period 1935–1964 (considered as the control in this case).

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

For each gauge and sub-period, the statistical moments were nominally predicted using Eq. (4) for the two versions of the model parameter settings (Table 2). We also compared these predictions with the case where the nominally predicted PDF for one sub-period was modelled using the statistical values calculated from the observed data of the other sub-period ('no model' case). The 'no model' case illustrates the 'stationary climate' scenario in which climate change is not taken into account, and thus the PDFs' parameters are not modified for the period of prediction. This case reflects the situation as considered in the guidelines for engineering hydrology (SP33-101-2003, 2004; Bulletin 17–B, 1982), when only the observed runoff timeseries were used to evaluate the PDF parameters. The percentage of nominally predicted PDFs that matched successfully to the empirical PDFs according to the Pearson chi-squared and Kolmogorov-Smirnov one-sample tests were evaluated for each version of the model parameterization. Table 3 provides the percentages of successful coincidences for the PDFs, which were obtained from the available cross-validation dataset (46 pairs of simulation and empirical PDFs).

The model with the constant parameters gives a more conforming result than the 'no model' case: the percentage of successfully matched PDFs is 5–10 percentage points higher. 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. Hereinafter, we used the regional-oriented parameterization scheme to estimate the future PDF parameters of the flood depth of runoff based on the climate change projections.

2.3 Data and method application

In performing the long-term assessment of the extreme flood events in the Russian Arctic, the period 1930 to 1980 was chosen as the reference period, while the projected period was from 2010 to 2039. The following datasets were used: (i) the climatology for the reference period (Fig. 4 a, b), (ii) the mean values and CV 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 climatology catalogs and the archives of the Arctic and Antarctic Research Institute, covering 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). For the precipitation, we use annual values although the spring floods are formed only by snowfall and spring rainfall. However, in the Arctic the relationship between spring flood depth of runoff and both annual and winter–spring sums of precipitation are strong (Shevnina, 2011).

The climatology for the projected period is provided by the climate models (Pachauri and Reisinger, 2007; Taylor et al., 2012). In this study, the projections of two Emissions Scenarios (SRES: A1B and B1) and two Representative Concentration Pathways (RCPs: 2.6 and 4.5) scenarios were extracted from CMIP3 and CMIP5

datasets. Results of climate models of 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 the Canadian Center for Climate Modelling Earth System Model CanESM2 (von Salzen et al., 2013) were used. These GCMs produce approximately similar climate projections. This allows to show that the hydrological modelling results do not vary much under slightly different climate forcing factors. To obtain the climate forcing, the projected mean values of air temperature and precipitation were corrected using the delta changes method (Fowler et al., 2007). For that, the relative changes in the variables (in degrees for the temperature and in % for precipitation) were first calculated based on the historical simulations and observed climatology for the reference period. Then these changes were added to/multiplied in the projected climatology. The corrected mean values of the annual precipitation and annual average air temperature were estimated for the nodes of the corresponding climate model grids.

The means and CVs of the spring flood depth of runoff were extracted from the maps of Rogdestvenskiy (1986) and Vodogretskiy (1986) in the following way by scanning the paper maps, image georeferencing, digitizing the data, and interpolating onto the grid nodes of the particular GCM. These maps were designed based on the observations for the period from the early 1930s up to 1980 (Rogdestvenskiy, 1988). In producing these maps, the observations on catchments of medium size (from 1000 to 50 000 km^2) located within the single climate zone were used. Thus, the features of runoff processes on the local scale (appearing on small watersheds) and the global scale (revealed on huge watersheds located within several climate zones) as well as floods due to ice jams and tides/surges were not considered. In our study, no timeseries of multi-year runoff were used to evaluate the mean value and CV for the reference period and no extrapolation was applied for the regions without observations.

The values of $\bar{c}$ and $G_{\widetilde{N}}$ were calculated using Eq. (3) for each node of the particular climate model grid. Then, the future first and the second initial statistical moments were calculated according to Eq. (4) using the projected climatology, and the future values of CV of the spring flood depth of runoff were evaluated. The future values of CS were estimated using the regional ration of $\mathrm{CS/CV}$ with the assumption that it is constant for the reference and projected period. The maximum discharge with the required exceedance probability was calculated according to Eq. (1) (see Section 3 for the example). Our study was performed for the period 2010–2039, since within this interval the existing and developing socio-economic infrastructure (bridges, oil/gas pipelines, roads and dams) will operate.

3. Result and discussion

The analysis of the expected climate change in Russia and particularly over the Arctic is provided by Govorkova et al. (2008) and Meleshko et al. (2008). These studies considered the territories of the Russian Federation as a whole. In our study, we provide the estimates for the geographical domain of the Russian Arctic, which was outlined according to the hydrological principles as suggested by Ivanov and Yankina (1991) and further used by Nikanorov et al. (2007).

The projected climatology averaged over the Russian Arctic is presented in Table 4 for the SRES and RCP scenarios. Generally, an increase of annual precipitation over 20 mm (6 %) and warming of over 2.1 °C were predicted according to the SRES scenarios. For the RCP scenarios, the changes were more pronounced, with the precipitation mean values expected to increase by more than 40 mm (12 %), accompanied by 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 means and CVs 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 slight decrease of CVs were predicted according to the SRES scenarios (Table 4). Using the scenarios of the Fifth Assessment Report, the changes in the statistics of the spring flood 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 CV's were expected. The strongest increase (over 45 mm or 27 %) of the means with a lowest decrease of the CVs (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 means of the spring flood depth of runoff (of 30–35 %) was predicted for Arkhangelsk Oblast and the 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 the Kola Peninsula and Karelia (Fig. 5a), accompanied by a decrease of CVs.

We can not compare our results with other studies directly because we address different flooding characteristics. Only an indirect comparison is possible. For the comparison, we assume that for the Pearson type III distribution, an increase in the means and CVs leads to an increase of upper-tail values. Subsequently, present 100-year floods will occur more frequently (Fig. 6). Also, a decrease in the means and CVs leads to a decrease in the upper-tail values. In this case, we can expect that the number of 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 CVs were estimated to increase in general 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). The flood frequency decreases in many regions of northern and eastern Europe according to Hirabayashi et al. (2013). The feasible reason for such disagreement is that the model used by Hirabayashi et al. (2013) is very coarse: it was calibrated using observations from watersheds larger than 100 000 km². 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 the 2020s, which is in accordance with our results.

For the Kola Peninsula and Karelia, we predicted a decrease in the mean values with a slight increase of the CVs according to the SRES:A1B and SRES:B1 scenarios. Dankers and Feyen (2008) suggested a strong decrease in 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 generally in agreement with our results. A similar tendency of decreasing maximal discharges was predicted for northern Finland (Veijalainen et al., 2010).

There are several sources of uncertainties in the method described above: (1) from the assumed (given a priori) type of distribution (Pearson type III); (2) from the limited length of hydrological timeseries that were used to evaluate the parameters of the distribution for the reference period; (3) from the limited length of meteorological timeseries to evaluate the climatology for the model parameterization; (4) from the uncertainties in future climatology provided by climate models (forcing); (5) from the mapping errors due to interpolation techniques; (6) from the errors due to the calculation of the maximal discharges from the spring flood depth of runoff (Eq. (1)). The uncertainties inherent in the simulated PDF parameters include items 1–5 from the list above. These uncertainties are evaluated by Kovalenko (1993) for the maps of means/CVs provided by Rogdestvenskiy (1986) and Vodogretskiy (1986) with the assumption that the errors in the future and past climatology are the same. The average percentage errors in the projected means/CVs are equal to 15 % / 25 %, thus it suggests considering the changes in the PDF parameters to be substantial if they exceed the reference values for more than these thresholds. The regions with substantial changes in the means and CVs of the spring flood flow depth are shown in Fig. 7.

In these regions, the frequency and magnitude of floods were predicted to differ substantially from the historical (reference) period. The changes in the mean values and coefficients of variation were predicted according to 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 Arkhangelsk Oblast, Komi Republic, and Eastern Siberia (see Fig. 8 for the boundary of the regions). These are warning regions where the flood-related risks for hydraulic constructions in the future may be different from the past. In these regions, calculations of the maximal discharges should be corrected in line with the expected climate change.

As an example, the climate-based correction for the Nadym River at Nadym City according to climate model outputs for the RCP 2.6 scenario is given below. A new bridge over the Nadym River was constructed in 2015 and repaired after the spring flood in 2016. The maximal discharge of rare occurrence (e.g. 1 % exceedance probability) is required to assess the bridge height and cost. The watershed of the Nadym River is located in the region, where the increase in the mean spring flood depth of runoff was predicted under RCP2.6 scenario (Fig. 7, right, upper plot). Thus, the climate change impacted upper-tail maximal discharge may be considerably larger than the value estimated from the observed timeseries. Hydrological observations for the Nadym River are available at Nadym City (gauge number 11805, the watershed area is 48 000 km^2, see the bottom panel of Fig. 8). The statistics of the spring flood depth of runoff for this gauge were calculated from observations in the period 1954–1980, which was considered as the 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 projected climatology with delta correction for the period 2010–2039 under the RCP 2.6 scenario was obtained from the CMIP5 dataset. The parameter $G_{\widetilde{N}}$ was estimated according to the observed climatology and the parameter $\overline{c}$ was calculated from the projected climatology according to Shevnina (2012). These values were used to predict the first and second initial

statistical moments, and the coefficient of variation (m_1, m_2 and CV) of the spring flood depth of runoff. The projected CS was estimated from the given ratio of CS/CV. The projected PDF was obtained from these values together with the spring flood depth of runoff 1 % exceedance probability ($h_{1\%}$, mm) (Table 6). The confidence intervals for the reference values of $h_{1\%}$ were calculated using the formulas suggested by Ashkar and Bobée (1988) in

400   assumption that the given distribution is Pearson type III. The 90 % confidence interval for the reference $h_{1\%}$ equal to ±64.5 mm, which is about 23 % of the quantile value. The projected values of $h_{1\%}$ are within these uncertainties for all considering climate scenarios (Table 6), thus due to the short timeseries we can not prove that the future changes in $h_{1\%}$ are statistically insignificant. However, we suggest taking it into account for the projected climatology when calculating hydrological risks due to practical reasons: it is better to prevent a disaster rather than to deal with its

405   consequences, which may be more expensive than the initial investment (Räisänen and Palmer, 2001). Finally, the maximal discharge with 1 % exceedance probability ($Q_{1\%}$, m³ s⁻¹) was estimated from $h_{1\%}$ according to Eq. (1). The values of the parameters in Eq. (1) were taken from the look-up tables (Guideline, 1984). The value of k_0 was considered to be constant for the reference and projected periods and set to be equal to 1 in our example, for the sake of simplicity; 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 (km²) and

410   n equals to 0.17.

For the period 2010–2039 the maximal discharge of 1 % exceedance probability, calculated with averaging of the multi-model output, is 570 m³ 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 m³ s⁻¹ changed the probability of exceedance from

415   1 % (calculated from the observations) to 2.5 % (calculated according to the averaged climate projections).

4. Conclusions

A probabilistic approach was applied in estimating the impact of climate change on the frequency and magnitude of extreme floods in the Russian Arctic. The projected meteorological mean values for periods of 20–30 years were used to estimate the future means, CVs and CSs of the spring flood depth of runoff, and to model the

420   PDFs with a Pearson type III distribution. The future frequency and magnitude of extreme floods with a required exceedance probability 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, however, in calculating multi-year timeseries of spring flood depth of runoff (and maximal discharge), the global and regional runoff databases may also be used. The examples of the datasets are (i) the

425   Global Runoff Data Centre, Germany; (ii) the Environmental Information System (HERTTA), Finnish Environment Institute; the Vattenwebb by the Swedish Meteorological and Hydrological Institute. To perform the assessments for other regions, the steps are as follows: (i) to choose the middle size watersheds with a catchment area from 1000 to 50 000 km²; (ii) to calculate the multi-year timeseries of runoff (yearly maximal discharges or flood depth of runoff) from the daily runoff timeseries; (iii) to select the time period without statistically

430 significant trends (reference period); (iv) to estimate the mean values, CVs and CSs from the observed timeseries of runoff or to evaluate them from the regional maps (i.e. Spence and Burke, 2008) and the statistics of the precipitation and air temperature; (v) to perform the model parameterization using general (Kovalenko et al., 2010) or regional-oriented schemes (Shevnina, 2012); (vi) to assess the mean values of the precipitation and air temperature from the results of the GCM/RCM models for the future; and (vii) to evaluate the future means,

435 CVs and CSs of multi-year runoff with Eq. (4). To perform the model cross-validation and to develop the regional-oriented parameterization scheme, the multi-year timeseries of runoff with periods of statistically significant shifts in the mean values and CVs 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 for a successful prediction of

440 67–83 % of the PDFs (see Section 2.2). The projected mean values, CVs and CSs 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 CVs were predicted depending on the scenarios considered. For the northwest Russian Arctic, an increase in the means and a decrease of the CVs were predicted.

445 The regions with substantial changes in the mean values (over 15 %) and CVs (over 25 %) were defined for 2010–2039. For territories where the means and CVs increased substantially, extreme floods are predicted to occur more frequently and the risk of flooding is increased. We suggest correcting the hydrological engineering calculations and accounting for the projected climatology. Such might reduce the risk of a potential hazard for hydraulic construction, the oil and gas industry, transport infrastructure, and population located in these

450 threatened regions.

The model presented in this study provides an affordable method to produce forecasts of extreme flood events (in the form of PDF or as maximal discharge with a required exceedance probability) under the projected climate change scenarios. This is possible due to the low numbers of simulated variables and parameters. The regionally-oriented parameterization of the model is also relatively simple and may be improved by involving a variance of

455 precipitation, which could be obtained from the projected climatology (Meehl et al., 2011). However, due to various simplifications, the model presented in this study does not allow for 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 provides an explicit advantage in estimating extreme hydrological events under altered climate, especially for regions with insufficient observational data. It could be useful for a broad-scale

460 assessment to define the threatened regions where a crucial increase/decrease of the extreme flood events is 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. Such models also allow for evaluating the value of the spring flood coincidence factor k_0 (Eq. (1)) for the projected periods (which was constant in our calculations). The evaluation and inter-comparison of the presented model and rainfall-runoff models

465 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 worldwide, these physiographic parameters may be derived from spatially distributed datasets, e.g. according to Bartholomé and Belward (2005). Also, an issue to be studied

470 is the effect of the spatial resolution of projected climatology on the ability of this model to estimate the frequency/magnitude of extreme floods for watersheds of different sizes.

The method described in this study was simplified for the use of engineering calculations, as the projected climatology for periods of 20–30 years as recommended by the IPCC (Pachauri and Reisinger, 2007) assumes a quasi-stationary climate. In general, the quasi-stationarity assumption may be eliminated and a non-stationary

475 regime could be considered. In this case, the PDFs 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).

Acknowledgements. This study was funded through the Ministry of Education and Science of the Russian

480 Federation (project 1413) and supported by the Academy of Finland (contract 283101). The article processing charges for this open-access publication were covered by the Academy of Finland. The authors are very thankful to the Reviewers of BER and HESS, who provided very useful comments and suggestions for improving the manuscript. Our special thanks to Lynn.

485 *Data availability.* Our study is based on third party data. The citations to the data sets have been included in the reference list.

Competing interests. The authors declare that they have no conflict of interest.

Annex.

490 The concept of probabilistic modeling to obtain a hydrological response to an expected climate change was proposed by Kovalenko (1993), it is presented further as provided in Kovalenko et al. (2010). This approach considers multi-year runoff timeseries (annual, maximal, and minimal) as realizations of a stochastic process of the Markov chain type (Rogdestvenskiy, 1988). Then, a first order ordinary differential equation is used as a lumped hydrological model for the multi-year flow timeseries:

495 $$dQ/dt = -(1/k\tau)Q + \dot{X}/\tau , \text{(A1)}$$

where Q is some runoff characteristic depending on a task (the discharge, the runoff volume per year, the runoff depth per year, *etc.* – 'model output'); $\dot{X}$ is the precipitation 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 during one year generates the runoff from the watershed during one year);

500 *t* is the time interval, equal to one year. Denoting $c = 1/k\tau$ and $N = \dot{X}/\tau$, and adding random components ($\widetilde{c}$, $\widetilde{N}$ stand for 'white noise') to $c = \bar{c} + \widetilde{c}$ and $N = \bar{N} + \widetilde{N}$ we obtain the stochastic differential equation:

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

The random components are mutually correlated.

The solution of Eq. (A2) is statistically equivalent to the solution of the Fokker-Planck-Kolmogorov equation (Pugachev et al., 1974):

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

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:

$$A(Q,t)=-\left(\bar{c}+0.5\mathrm{G}_{\widetilde{c}}\right)Q-0.5\mathrm{G}_{\widetilde{c}\widetilde{N}}+\bar{N} \quad ;$$

$$B(Q,t)=\mathrm{G}_{\widetilde{c}}Q^2-2Q\mathrm{G}_{\widetilde{c}\widetilde{N}}+\mathrm{G}_{\widetilde{N}} \quad \text{, (A4)}$$

here, $\mathrm{G}_{\widetilde{c}}$ and $\mathrm{G}_{\widetilde{N}}$ are the measures of variability of c and N; $\mathrm{G}_{\widetilde{c}\widetilde{N}}$ is the measure of correlation between the variability of $\mathrm{G}_{\widetilde{c}}$ and $\mathrm{G}_{\widetilde{N}}$.

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):

$$dm_1/dt=-\left(\bar{c}-0.5\mathrm{G}_{\widetilde{c}}\right)m_1-0.5\mathrm{G}_{\widetilde{c}\widetilde{N}}+\bar{N};$$
$$dm_2/dt=-2\left(\bar{c}-\mathrm{G}_{\widetilde{c}}\right)m_2+2\bar{N}m_1-3\mathrm{G}_{\widetilde{c}\widetilde{N}}m_1+\mathrm{G}_{\widetilde{N}}; \qquad \text{(A5)}$$
$$dm_3/dt=-3\left(\bar{c}-1.5\mathrm{G}_{\widetilde{c}}\right)m_3+3\bar{N}m_2-7.5\mathrm{G}_{\widetilde{c}\widetilde{N}}m_2+3\mathrm{G}_{\widetilde{N}}m_1.$$

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 $C_s=\left(m_3-3m_2m_1+2m_1^3\right)/\left(C_v^3m_1^3\right)$. In this study, the constant value of the CS/CV ratio for the projected time period was used to simplify Eq. (A5). This assumption is commonly applied in engineering hydrological applications to estimate the regional CS (Guideline, 1974). Also, the climate scenarios are distributed by IPCC as mean values of meteorological variables for periods of 20–30 years. Thus, scenarios for the expected climate change are presented with an assumption of 'quasi-stationarity' and this may also be applied to the hydrological regime. This allows further simplifications of Eq. (A5): $dm_i/dt\approx0$ and $\mathrm{G}_{\widetilde{c}},\mathrm{G}_{\widetilde{c}\widetilde{N}}=0$ within these periods. Hence, Eq. (A5) may be reduced to only 2 algebraic equations for m_1 and m_2:

$$-\bar{c}m_1+\bar{N}=0$$
$$-2\bar{c}m_2+2\bar{N}m_1+\mathrm{G}_{\widetilde{N}}=0 \quad .$$

This system may be applied to estimate the multi-year hydrological statistical moments directly from climatology for each 'quasi-stationary' time period.

530   **References**

Archeimer, B. and Lindström, G.: Climate impact on floods: changes in high flow in Sweden in the past and the future (1911–2100), Hydrol. Earth Syst. Sc., 19(2), 771–784, doi: 10.5194/hess-19-771-2015, 2015.

Ashkar, F. and Bobée, B.: Confidence intervals for flood events under a Pearson 3 or log Pearson 3 distribution. J. Am. Water Resour. Assoc., 24: 639–650. doi: 10.1111/j.1752-1688.1988.tb00916.x, 1988.

535   Benson, M.A.: Uniform flood frequency estimating methods for federal agencies. Water Resource Research, 4, 891–908, 1968.

Bertholome´, E. and Belward, A. S.: GLC2000: a new approach to global land cover mapping from Earth observation data, Int. J. Remote Sens., 26(9), 1959–1977, doi: 10.1080/01431160412331291297, 2005.

Bowman, K.O. and Shenton, L.R.: Estimator: Method of Moments, in: Encyclopedia of statistical sciences,
540   Wiley, New York, 2092–2098, 1998.

Bulletin 17–B: Guideline for determining flood flow frequency, U.S. Geological Survey, Virginia, 1982.

Catalogue of climatology of USSR Serie 3: multi-year data, Gidrometeoizdat, Leningrad, 1989. (In Russian).

Collins, W. J., Bellouin N., Doutriaux-Boucher M., Gedney N., Hinton, T., Jones, C. D., Liddicoat, S., O'Connor M. G. F., Rae, J., Senior, C., Totterdell, I., Woodward, S., Reichler, T. and Kim, J.: Evaluation of the
545   HadGEM2 model. Met Office Hadley Centre Technical Note no. HCTN 74, 2008.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J. and Wehner, M.: Long-term Climate Change: Projections, Commitments and Irreversibility, in: Climate Change: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change,
550   Cambridge University Press, Cambridge, United Kingdom and New York, 1029–1136, 2013.

Dankers, R. and Feyen, L.: Climate change impact on food hazard in Europe: an assessment based on high-resolution climate simulations, J. Geophys. Res.-Atmos., 113, D19105, doi:10.1029/2007JD009719, 2008.

Delworth, T. L., Broccoli, A. J., Rosati, A., Stouffer, R. J., Balaji, V., Beesley, J. A., Cooke, W. F., Dixon, K. W., Dunne, J., Dunne, K. A., Durachta, J. W., Findell, K. L., Ginoux, P., Gnanadesikan, A., Gordon, C. T.,
555   Griffies, S. M., Gudgel, R., Harrison, M. J., Held, I. M., Hemler, R. S., Horowitz, L. W., Klein, S. A., Knutson, T. R., Kushner, P. J., Langenhorst, A. R., Lee, H.-C., Lin S.-J., Lu J., Malyshev, S. L., Milly, P. C. D., Ramaswamy, V., Russell, J. M., Schwarzkopf, D., Shevliakova, E., Sirutis, J. J., Spelman, M. J., Stern, W. F., Winton, M., Wittenberg, A. T., Wyman, B., Zeng, F., and Zhang, R.: GFDL's CM2 global coupled climate models. Part 1: Formulation and simulation characteristics, J. Climate, 19 (5), 643–674, 2006.

560   Domínguez, E. and Rivera, H.: A Fokker–Planck–Kolmogorov equation approach for the monthly affluence forecast of Betania hydropower reservoir, J. Hydroinform., 12(4), 486–501, 2010.

Ducré-Robitaille, J.-F., Vincent, L. A. and Boulet, G.: Comparison of techniques for detection of discontinuities in temperature series, Int. J. Climatol., 23(9), 1087–1101, doi: 10.1002/joc.924, 2003.

Elderton, S.W.P., and Johnson, N.L.: Systems of Frequency Curves, Cambridge University Press, London, 1969.

565   Fowler, H. J., Blenkinsop, S. and Tebaldi, C.: Linking climate change modeling to impacts studies: recent advances in down-scaling techniques for hydrological modelling, Int. J. Climatol., 27(12), 1547–1578, 2007.

Gazprom: available at www.gazprom.com/about/production/projects/mega-yamal, 2017.

570 Giorgetta, M., Jungclaus, J., Reick, C., Legutke, S., Bader, J., Böttinger, M., Brovkin, V., Crueger, T., Esch, M., Fieg, K., Glushak, K., Gayler, V., Haak, H., Hollweg, H.-D., Ilyina, T., Kinne, S., Kornblueh, L., Matei, D., Mauritsen, T., Mikolajewicz, U., Mueller, W., Notz, D., Pithan, F., Raddatz, T., Rast, S., Redler, R., Roeckner, E., Schmidt, H., Schnur, R., Segschneider, J., Six, K., Stockhause, M., Timmreck, C., Wegner, J., Widmann, H., Wieners, K.-H., Claussen, M., Marotzke, J. and Stevens, B.: Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the coupled model intercomparison project phase 5. J. Adv. Model. Earth Sy., 5, 572-597, doi:10.1002/jame.20038, 2013.

575 Govorkova, V. A., Katsov, V. M., Meleshko, V. P., Pavlova, T. V. and Shkol'nik, I. M.: Climate of Russia in the 21st Century. Part 2. Verification of atmosphere-ocean general circulation models CMIP3 for projections of future climate changes, Russ. Meteorol. Hydrol., 33(8), 467–477, 2008.

Guideline SP33–101–2003: to estimate basic hydrological characteristics, Gosstroy, Moscow, 2004. (In Russian).

Guideline to estimate basic hydrological characteristics, Gidrometeoizdt, Leningrad, 1984. (In Russian).

580 Hirabayashi, S., Kanae, S., Emori, T., Oki, T. and Kimoto, M.: Global projections of changing risks of foods and droughts in a changing climate, Hydrolog. Sci. J., 53(4), 754–773, 2008.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H. and Kanae, S.: Global flood risk under climate change, 816–821, 2013.

Hofierka, J., Parajka, J., Mitasova, H. and Mitas, L.: Multivariate interpolation of precipitation using regularized 585 spline with tension, Transaction in GIS, 6(2), 135–150, 2002.

Hollander, M., Wolfe, D.A. and Chicken, E.: Nonparametric statistical methods, 3d edition, Wiley, New Jersey, 848 p., 2014.

IPCC, The Physical Basis, Annex I: Atlas of Global and Regional Climate Projections, Cambridge University Press, New York, 2013.

590 Ivanov, V. and Yankina, V.: Water resources of the Arctic: the past and future aims of research, Problem of Arctic and Antarctic, 66, 118–128, 1991. (In Russian).

Johns, T.C., Gregory, J. M., Ingram, W. J., Johnson, C. E., Jones, A., Lowe, J. A., Mitchell, J. F. B., Roberts, D. L., Sexton, B. M. H., Stevenson, D. S., Tett, S. F. B. and Woodage, M. J.: Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios, Clim. Dyn., 20, 583– 595 612, 2003.

Kharin, V.V., Zwiers, F.W., Zhang X. and Wehner M.: Changes in temperature and precipitation extremes in the CMIP5 ensemble, Climatic Change, 119, 345–357, doi: 10.1007/s10584-013-0705-8, 2013.

Kite, G.W.: Frequency and risk analysis in hydrology, Fort Collins, Colorado, 1977.

Kovalenko, V. V.: Modeling of hydrological processes, Gidrometizdat, Sankt-Peterburg, 1993. (In Russian).

600 Kovalenko, V.V.: Using a probability model for steady long-term estimation of modal values of long-term river runoff characteristics, Russ. Meteorol. Hydrol., 39(1), 57–62, 2014.

Kovalenko, V. V., Victorova, N. V., Gaydukova, E. V., Gromova, M. A., Khaustov, V. A. and Shevnina, E. V.: Guideline to estimate a multi-year runoff regime under non-steady climate to design hydraulic contractions, RSHU, Sankt-Petersburg, 2010. (In Russian).

605 Krasting, J. P., Broccoli, A. J., Dixon, K. W. and Lanzante J. R.: Future Changes in Northern Hemisphere Snowfall, J. Climate, 26, 7813–7828, doi:10.1175/JCLI-D-12-00832, 2013.

Kritsky, S.N. and Menkel, M.F.: On the methods of studying the random variations of river flow, Gidrometeoizdat, 1946. (In Russian).

Kuchment, L.S. and Gelfan, A.N.: Assessment of extreme flood characteristics based on a dynamic-stochastic

610 model of runoff generation and the probable maximum discharge. Journal of Flood Risk Management, 4, 115–127, 2011.

Kuznetsov, I. V. (Eds.): Multi-year book of basic hydrological characteristics, Gidrometeoizdat, Leningrad, 1966. (In Russian).

Laine, A., Nakamura, H., Nishii, K. and Miyasaka T.: A diagnostic study of future evaporation changes projected

615 in CMIP5 climate models, Clim. Dyn., 42, 2745-2761, doi:10.1007/s00382-014-2087-7, 2014.

Lawrence, D. and Haddeland, I.: Uncertainty in hydrological modeling of climate change impacts in four Norwegian catchments, Hydrol. Res., 42(6), 457–471, doi: 10.2166/nh.2011.010, 2011.

Lehner, B., Döll, P., Alcamo, J., Henrichs, H. and Kaspar, F.: Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis, Climatic Change, 75, 273–299,

620 doi:10.1007/s10584-006-6338-4, 2006.

Lins, H. F. and Cohn, T. A.: Stationarity: Wanted Dead or Alive? J. Am. Water Resour. As., 47(3), 475–480, doi:10.1111/j.1752-1688.2011.00542.x, 2011.

Mackenzie gas project: available at http://www.mackenziegasproject.com, 2017.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M. and Kjeldsen, T.R.:. A review of applied methods in

625 Europe for flood-frequency analysis in a changing environment. NERC/Centre for Ecology & Hydrology on behalf of COST, http://nora.nerc.ac.uk/501751/ (last access: 2 February 2017), 2013.

Meehl, G.A. and Bony, S.: Introduction to CMIP5, CLIVAR Exchanges Newsletters, 56(16), 2–5, 2011.

Meleshko, V. P., Katsov, V. M., Govorkova, V. A., Sporyshev, P. V., Shkol'nik, I. M. and Shneerov, B. E.: Climate of Russia in the 21st century. Part 3. Future climate changes calculated with an ensemble of coupled

630 atmosphere-ocean general circulation CMIP3 models, Russ. Meteorol. Hydrol., 33(9), 541–552, 2008.

Milly, P., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P. and Stouffer, R. J.: Stationarity is dead: whither water management, Science, 319, 573–574, doi: 10.1126/science.1151915, 2008.

Montanari, A. and Koutsoyiannis, D.: Modeling and mitigating natural hazards: Stationarity is immortal! Water

635 Resour Res, 50 (12), 9748–9756, doi: 10.1002/2014WR016092, 2014.

Nikanorov, A.M., Ivanov, V.V., and Bryzgalo V.A.: The rivers of the Russian Arctic, the current conditions under the human impact, NOC, Rostov-on-Don, 2007. (In Russian).

Pachauri, R.K and Reisinger, A. (Eds.): Synthesis Report, Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, 2007.

640 Radionov, V. F. and Fetterer F.: Meteorological Data from the Russian Arctic 1961-2000, National Snow and Ice Data Center, Boulder, USA, 2003.

Razuvayev, V. N., Apasova, E.G., Martuganov, R. A., Steurer, P. and Vose, R.: CD-ROM daily temperature and precipitation data for 223 U.S.S.R. stations, ORNL/CDIAC, Oak Ridge National laboratory, Tennessee, 1993.

Petrowiki: available at http://petrowiki.org/Prudhoe_Bay_field, 2017.

645 Prowse, T., Bring, A., Mård, J., Carmack, E., Holland, M., Instanes, A.,Vihma, T. and Wrona F. J.: Arctic Freshwater Synthesis: Summary of key emerging issues, J. Geophys. Res. Biogeosci., 120, 1887–1893, doi:10.1002/2015JG003128, 2015.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta M., Hagemann, S.,Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese U., Schulzweida, U. and Tompkins, A.: The atmospheric

650 general circulation model ECHAM5. Part I: Model description. Max Planck Institute for Meteorology Rep. 349, 2003.

Rogdestvenskiy, A. V.: Map of the variation coefficient of the spring flood flow depth (map #8), in: Atlas of a hydrological maps and nomograms, Gidrometeoizdt, Leningrad, 1986. (In Russian).

Rogdestvenskiy, A. V.: Spatial and temporal variations of river flow in USSR, Gidrometeizdat, Leningrad, 1988.

655 (In Russian).

Rogdestvenskiy, A. V., and Saharyuk, A. V.: Generalization of Student and Fisher criteria for correlated in time and space hydrological timeseries, Letters of State Hydrological Institute, 282, 51–71, 1981. (In Russian).

Räisänen J. and Palmer T.N.: A probability and decision-model analysis of a multi model ensemble of climate change situations. J. Climate. 14: 3212–3226, 2001.

660 Pugachev, V.S., Kazakov, I.E. and Evlanov, L.G.: Basics of statistical theory of automatic system. Moscow, Mashinostroenie, 400, 1974. (In Russian).

Serinaldi, F. and Kilsby, C. G.: Stationarity is undead: Uncertainty dominates the distribution of extremes, Adv. Water Res., 77, 17, doi: 10.1016/j.advwatres.2014.12.013, 2015.

Shevnina, E.V.: The relationships between an annual and winter precipitation amount and flooding runoff on the

665 rivers over the Russian Arctic. Scientific reports of the Russian State Hydrometeorological University, 20, 6–12, 2011. (in Russian).

Shevnina, E. V.: The stochastic model validation using observed timeseries: multi-year statistics of spring flood flow depth, Problem of Arctic and Antarctic, (93), 40–50, 2012. (In Russian).

Sillmann, J., Kharin, V. V., Zwiers, F. W., Zhang, X. and Bronaugh, D.: Climate extremes indices in the CMIP5

670 multimodel ensemble: Part 2, Future climate projections, J. Geophys. Res. Atmos., 118, 2473–2493, 2013.

Spence, C. and Burke, A.: Estimates of Canadian Arctic Archipelago Runoff from Observed Hydrometric Data, J. Hydrol., 362, 247–259, doi: 10.1016/j.jhydrol.2008.08.019, 2008.

Taylor, K.E., Stouffer, R.J. and Meehl, G.A.: An overview of CMIP5 and the experiment design, B. Am. Meteorol. Soc., 93, 485–498, doi: 10.1175/BAMS-D-11-00094.1, 2012.

675 Tebaldi, C. and Knutti, R.: The use of the multi-model ensemble in probabilistic climate projections. Phil. Trans. R. Soc. A, 365, 2053–2057, 2007.

Thomas, W. J.: A Uniform Technique for Flood Frequency Analysis, Journal Water Resource Planning Management, 111(3), 321–337, 1985.

Toreti, A., Naveau, P., Zampieri, M., Schindler, A., Scoccimarro, E., Xoplaki, E., Dijkstra, H. A., Gualdi, S. and Luterbacher, J.: Projections of global changes in precipitation extremes from Coupled Model Intercomparison Project Phase 5 models, Geophys. Res. Lett., 40, 4887–4892, doi: 10.1002/grl.50940, 2013.

Veijalainen, N., Lotsari, E., Alho, P., Vehviläinen, B. and Käyhkö, J.: National scale assessment of climate change impacts on flooding in Finland, J. Hydrol., 391, 333–350, 2010.

Verzano, K.: Climate change impacts on flood related hydrological processes: further development and application of a global scale hydrological model, Reports on Earth system science 71, Max Planck Institute for Meteorology, Hamburg, 2009.

Viktorova, N. V. and Gromova, M. N.: Long-term forecasting of characteristics of minimal river runoff discharges in Russia in case of possible climate change, Russ. Meteorol. Hydrol., 33(6), 388–393, 2008.

Vodogretskiy, V.: Map of the mean values of the spring flood flow depth (map #6), in: Atlas of a hydrological maps and nomograms, Gidrometeoizdat, Leningrad, 1986. (In Russian).

von Salzen, K., Scinocca, J. F., McFarlane, N. A, Li, J., Cole, J. N. S., Plummer, D., Verseghy, D., Reader, M. C., Ma, X., Lazare, M., Solheim, L.: The Canadian Fourth Generation Atmospheric Global Climate Model (CanAM4). Part I: Representation of Physical Processes, Atmosphere-Ocean, 51, 104–125, doi:10.1080/07055900.2012.755610, 2013.

695 **Table 1.** Sub-periods with the statistically significant shift in the mean values of the spring flood depth of runoff with the multi-year statistics and climatology.

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

Gauge ID	River	Catchment area [km²]	Period	m_1 [mm]	m_2 [mm²]	CV	CS/CV	$\bar{N}$ [mm]	$\bar{T}$ [°C]
01176	Bohapcha	13600	1934–1949	111	15 401	0.50	2.5	421	−12.1
			1950–1980	141	23 907	0.45	2.8	435	−12.4
01309	Seimchan	2920	1941–1956	190	40 779	0.36	3.1	373	−11.5
			1957–1977	157	25 842	0.22	5.1	305	−11.4
01623	Srednekan	1730	1935–1950	148	25 067	0.38	4.0	426	−10.7
			1951–1980	180	36 145	0.34	4.5	431	−11.1
03403	Malaya Kuonapka	2030	1943–1985	97.5	10 848	0.36	0.8	255	−13.8
			1986–2002	116	14 297	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	56 198	0.21	1.3	491	−7.4
			1971–1999	260	70 304	0.20	1.4	494	−7.4
11574	Pyakupur	31400	1954–1970	142	21 140	0.22	4.2	482	−6.4
			1971–2001	162	27 884	0.23	3.7	514	−6.0
11805	Nadym	48000	1955–1974	162	27 632	0.23	3.0	490	−6.4
			1975–1991	140	21 607	0.32	2.2	471	−5.0
70047	Solza	1190	1928–1958	190	38 356	0.25	0.9	525	1.3
			1959–1980	155	26 046	0.29	0.8	552	1.0
70153	Yug	15200	1931–1946	126	16 716	0.23	2.0	575	1.6
			1947–1980	144	22 994	0.33	1.4	591	1.6
70180	Vychegda	26500	1930–1956	147	22 960	0.25	0.0	491	−0.1
			1957–1980	167	29 632	0.25	0.0	550	−0.5
70360	Lodma	1400	1939–1958	219	53 184	0.33	1.2	533	0.7
			1959–1977	174	32 650	0.28	1.4	546	0.7
70366	Kuloy	3040	1927–1958	134	20 549	0.38	1.4	467	1.0
			1959–1980	110	13 582	0.35	1.5	446	0.6
70410	Pechora	9620	1914–1930	302	94 159	0.18	-0.4	516	−1.0
			1931–1993	276	79 535	0.21	-0.3	564	−1.0
70414	Pechora	29400	1938–1956	250	65 806	0.23	0.5	490	−1.0

Gauge ID	River	Catchment area [km^2]	Period	m_1 [mm]	m_2 [mm^2]	CV	CS/CV	$\bar{N}$ [mm]	$\bar{T}$ [°C]
			1957–1980	278	79 262	0.16	0.8	601	−1.3
70466	Usa	2750	1936–1957	385	155 399	0.22	1.5	483	−4.3
			1958–1980	424	185 601	0.18	1.8	558	−5.3
70509	Izhma	15000	1933–1949	189	37 779	0.24	0.1	465	−0.5
			1950–1980	160	26 839	0.22	0.1	534	−0.9
70522	Ukhta	4290	1934–1949	170	30 706	0.25	0.9	473	−0.5
			1950–1980	144	22 032	0.25	0.9	535	−0.5
70531	Pizhma	4890	1937–1964	129	18 041	0.29	0.9	486	−1.7
			1965–1980	150	24 264	0.28	0.9	552	−2.3
71104	Kola	3780	1928–1958	182	35 539	0.27	2.6	350	0.5
			1959–1994	203	43 785	0.25	2.6	459	0.1
71199	Umba	6920	1931–1958	180	34 762	0.27	0.6	414	−1.1
			1959–1994	149	23 942	0.28	0.6	475	−1.6
71241	Yena	1600	1934–1948	100	10 625	0.25	0.7	451	0.2
			1949–1980	129	18 041	0.29	0.7	557	−0.3

700

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

705

Gauge ID	Lat/Lon	Period	$G_{\tilde{N}f}$ [mm^2]	$\bar{c}_f$	m_{1f} [mm]	m_{2f} [mm^2]	CV$_f$	CS$_f$
01176	62°06′N / 150°37′E	1934–1949	23366	3.79	115	16 234	0.48	1.20
		1950–1980	24841	3.09	136	22 647	0.46	1.28
01309	63°17′N / 152°02′E	1941–1956	18370	1.96	155	28 815	0.44	1.38
		1957–1977	4635	1.94	141	20 941	0.25	1.26
01623	62°22′N / 152°20′E	1935–1950	18208	2.88	150	25 584	0.38	1.50
		1951–1980	17936	2.39	178	35 398	0.34	1.54
03403	70°11′N / 113°57′E	1943–1985	6477	2.60	101	11 383	0.35	0.27
		1986–2002	3799	2.26	113	13 587	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 /	1941–1970	10047	2.12	233	56 857	0.21	0.27

Gauge ID	Lat/Lon	Period	$G_{\tilde{N}f}$ [mm²]	$\bar{c}_f$	m_{1f} [mm]	m_{2f} [mm²]	CV_f	CS_f
	84°17′E	1971–1999	10275	1.90	258	69 485	0.20	0.27
11574	64°56′N / 77°48′E	1954–1970	6625	3.39	151	23 906	0.21	0.86
		1971–2001	10408	3.17	152	24 718	0.27	0.27
11805	65°39′N / 72°42′E	1955–1974	8398	3.02	156	25 636	0.24	0.72
		1975–1991	13505	3.36	146	23 220	0.31	0.66
70047	64°41′N / 39°32′E	1928–1958	12469	2.76	200	42 164	0.24	0.21
		1959–1980	14391	3.56	147	23 753	0.30	0.23
70153	60°12′N / 47°00′E	1931–1946	7665	4.56	130	17 612	0.22	0.46
		1947–1980	18536	4.10	140	21 886	0.34	0.48
70180	61°52′N / 53°49′E	1930–1956	9022	3.34	165	28 465	0.22	−0.01
		1957–1980	11481	3.29	149	23 969	0.28	−0.01
70360	64°25′N / 41°03′E	1939–1958	25423	2.43	224	55 552	0.32	0.38
		1959–1977	14897	3.14	170	31 225	0.29	0.40
70366	64°59′N / 43°42′E	1927–1958	18073	3.49	128	18 970	0.40	0.55
		1959–1980	12020	4.05	115	14 749	0.33	0.51
70410	61°52′N / 56°57′E	1914–1930	10098	1.71	330	111 916	0.16	−0.06
		1931–1993	13730	2.04	253	67 121	0.23	−0.08
70414	62°57′N / 56°56′E	1938–1956	12960	1.96	307	97 330	0.19	0.10
		1957–1980	8554	2.16	227	53 351	0.20	0.15
70466	66°36′N / 60°52′E	1936–1957	18000	1.25	445	205 006	0.19	0.29
		1958–1980	15331	1.32	367	140 521	0.21	0.38
70509	63°49′N / 53°58′E	1933–1949	10124	2.46	217	49 166	0.21	0.03
		1950–1980	8271	3.34	139	20 651	0.25	0.03
70522	63°35′N / 53°51′E	1934–1949	10051	2.78	192	38 779	0.22	0.19
		1950–1980	9630	3.72	127	17 504	0.28	0.25
70531	65°17′N / 51°55′E	1937–1964	10545	3.77	147	22 867	0.26	0.23
		1965–1980	12983	3.68	132	10 205	0.32	0.30
71104	68°56′N / 30°55′E	1928–1958	9287	1.92	239	59 383	0.21	0.13
		1959–1994	11647	2.26	155	26 536	0.33	0.85
71199	66°52′N / 33°20′E	1931–1958	10865	2.30	207	45 013	0.24	0.15
		1959–1994	11098	3.19	130	18 606	0.32	0.24
71241	67°18′N / 32°08′E	1934–1948	5638	4.51	124	15 878	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 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 (CV)	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 annual precipitation; $\bar{T}$ is the mean annual air temperature; m_1 is the mean spring flood depth of runoff; CV is the coefficient of variation of the spring flood depth of runoff.

Dataset	Scenario	GCM	$\bar{N}$, [mm]	$\bar{T}$, [°C]	m_1, [mm]	CV
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 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 annual precipitation; $\bar{T}$ is the mean annual air temperature; m_1 is the mean spring flood depth of runoff; CV is the coefficient of variation of the spring flood depth of runoff, $h_{1\%}$ is the spring flood depth of runoff with exceedance of 1 %, $Q_{1\%}$ is the maximal discharge with exceedance probability of 1 %.

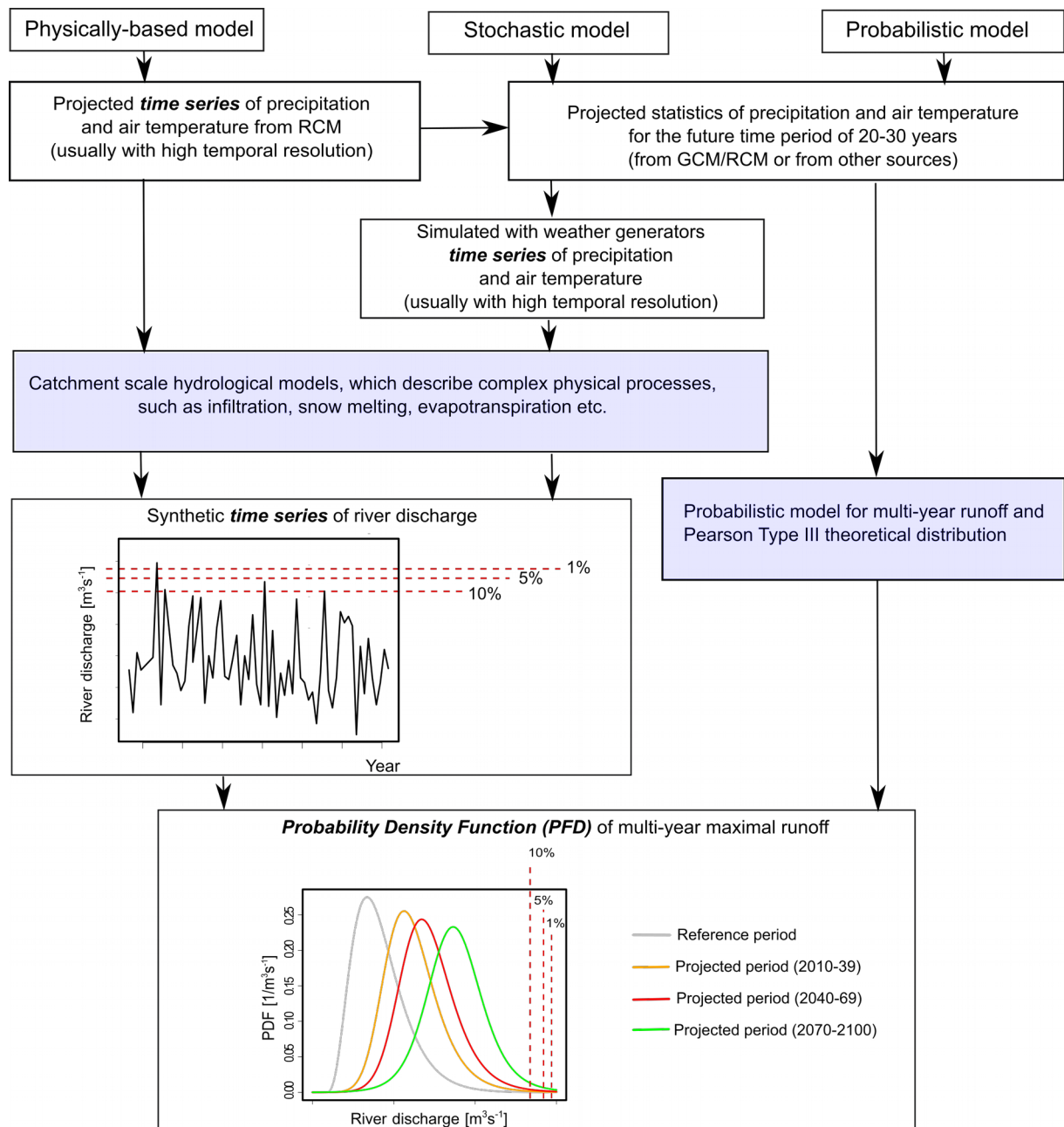
Multi-year values	Period of 1954–1980	Result according to GCM			
		HadGEM2-A	MPI-ESM-LR	CanESM2	Multi model
$\bar{N}$ mm	431	483	491	519	498
$\bar{T}$ °C	−5.9	−4.0	−2.9	−2.4	−3.1
m_1 mm	160	180	184	197	187
CV	0.28	0.25	0.23	0.19	0.22
$h_{1\%}$ mm	277	297	293	297	296
$Q_{1\%}$ m³ s⁻¹	8572	9177	9062	9191	9144

720

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

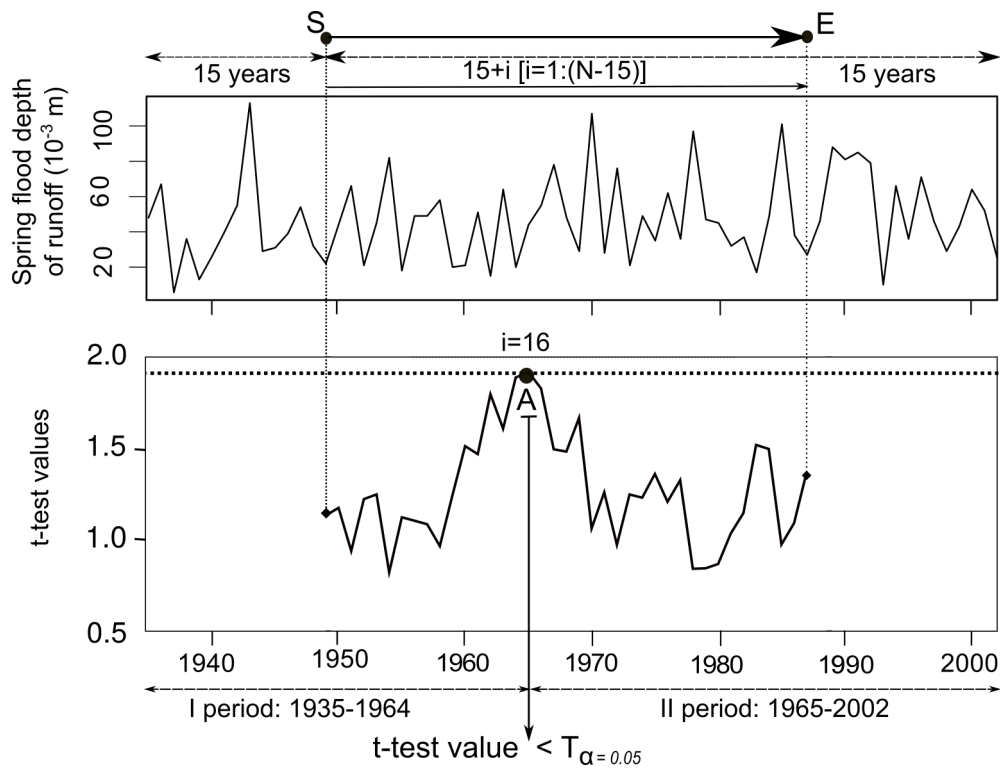



Figure 2. The partition of the observed timeseries of the spring flood depth of runoff (top) into sub-periods with a statistically significant shift in the mean value by the *t*-test (bottom) for the Yana River at Verkhoyansk City gauge: $T_{\alpha=0.05}$ is the critical value of the *t*-test at the threshold of statistical significance equal to 0.05 (dotted line on the bottom). See the text for the explanation of A, S, E, N and i.

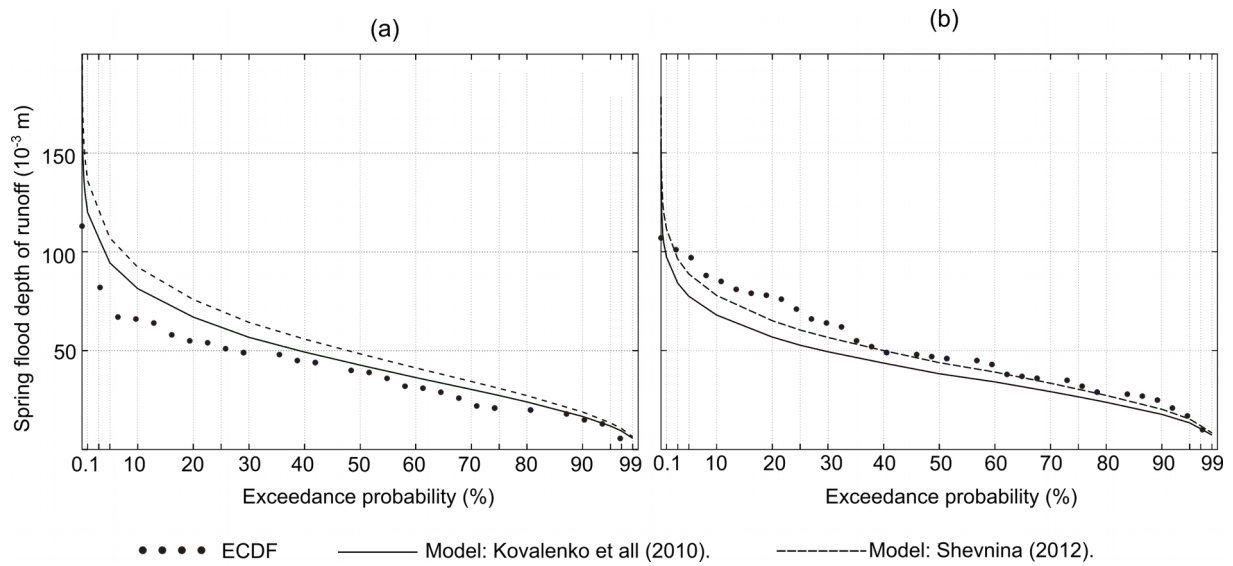



Figure 3. The nominally predicted exceedance probability curves compared with the empirical exceedance probability (ECDF) for the sub-periods with statistically significant shift in the mean value for the Yana River at Verkhoyansk City: (a) the period 1935–1964; (b) the period 1965–2002.

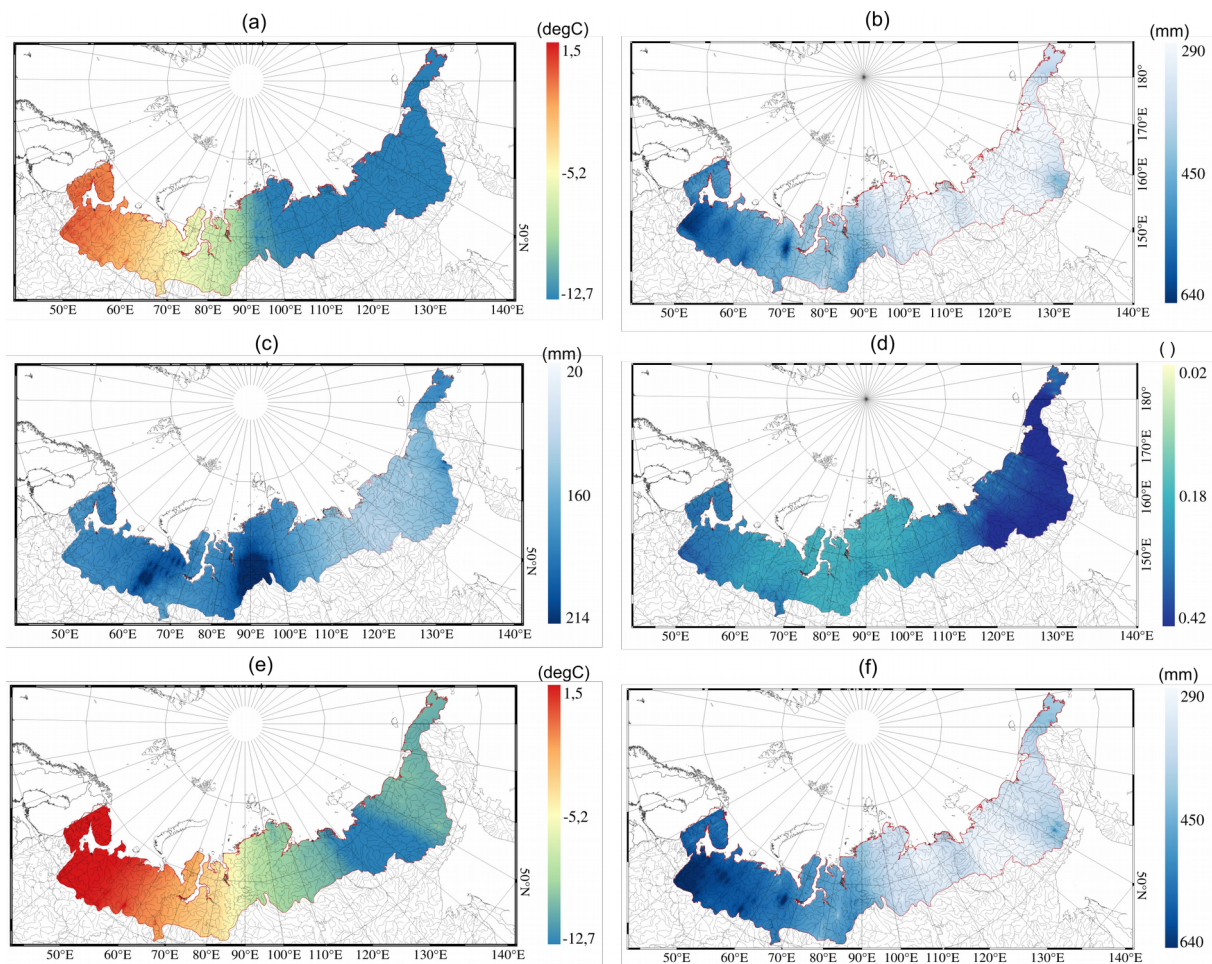



Figure 4. The data used in the study: (a) the mean values of annual air temperature for the reference period (Radionov and Fetterer, 2003; Catalogue, 1989); (b) the mean values of the annual precipitation for the reference period (Radionov and Fetterer, 2003; Catalogue, 1989); (c) the mean values of 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 air temperature for the projected period (2010– 2039) under the RCP 4.5, average of four GCMs (Taylor et al., 2012); (f) the mean values of the annual precipitation 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 Ivanov and Yankina (1991).

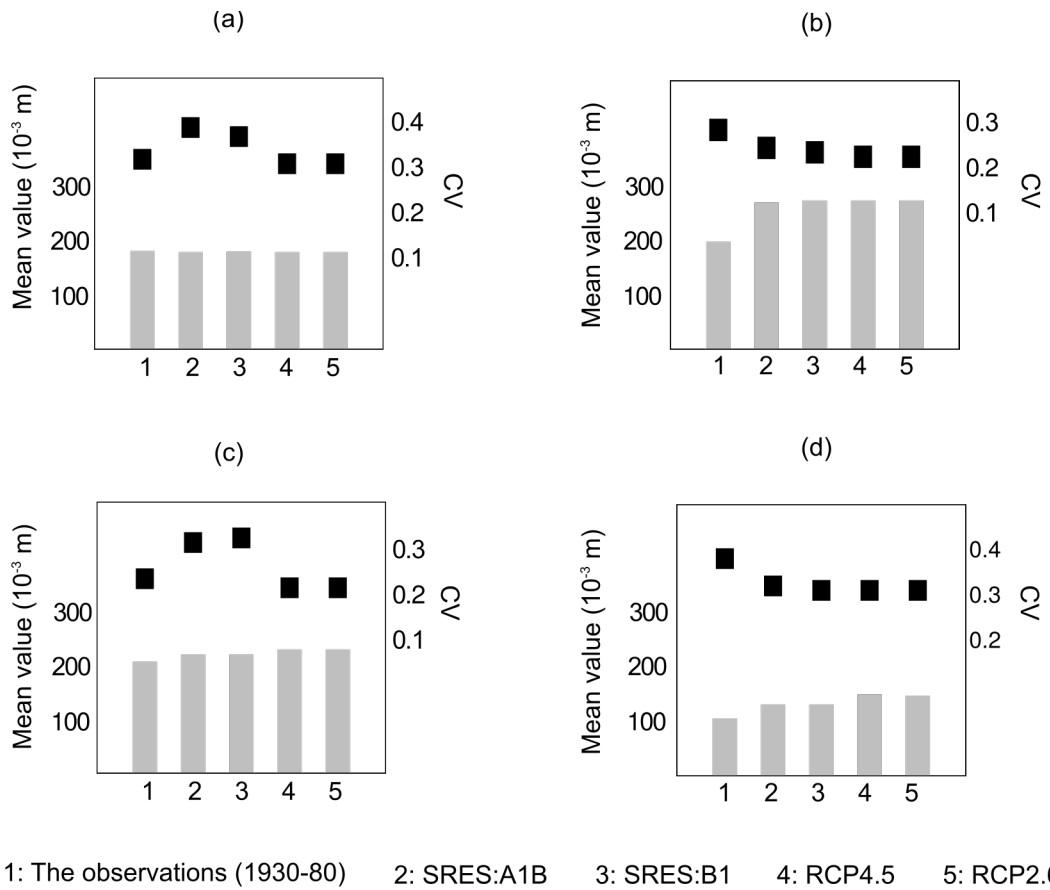



Figure 5. The observed and projected the mean values (bars) and coefficients of variation (squares) of the spring flood depth of runoff expected for the regions of the Russian Arctic for the period 2010–2039: (a) – the Kola Peninsula and Karelia, (b) – Arkhangelsk Oblast and the Komi Republic; (c) – West Siberia; (d) – East Siberia.

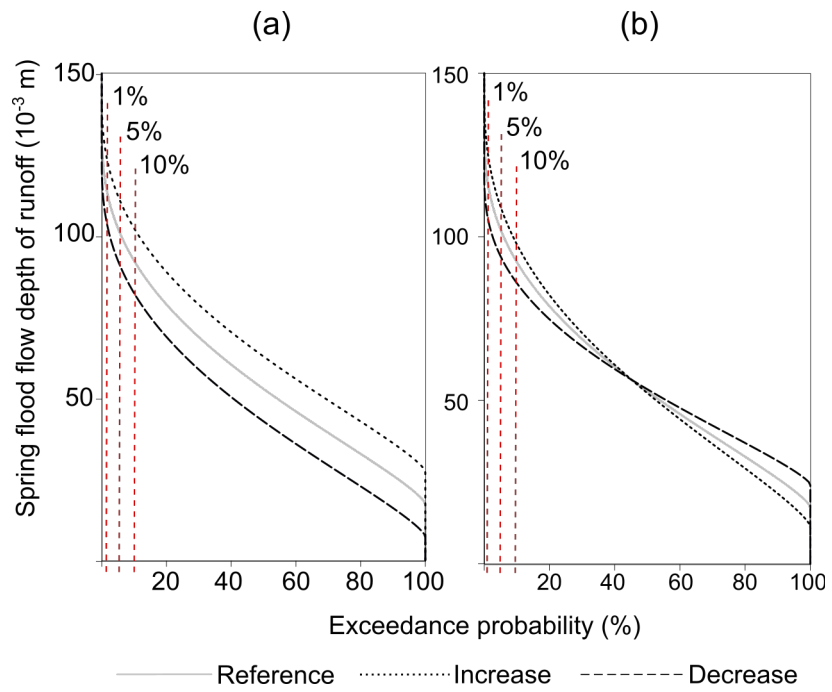



Figure 6. Schematic explanation of the changes in the upper-tail values due to changes in the parameters of the exceedance probability curve: (a) – the mean value and (b) – the coefficient of variation.

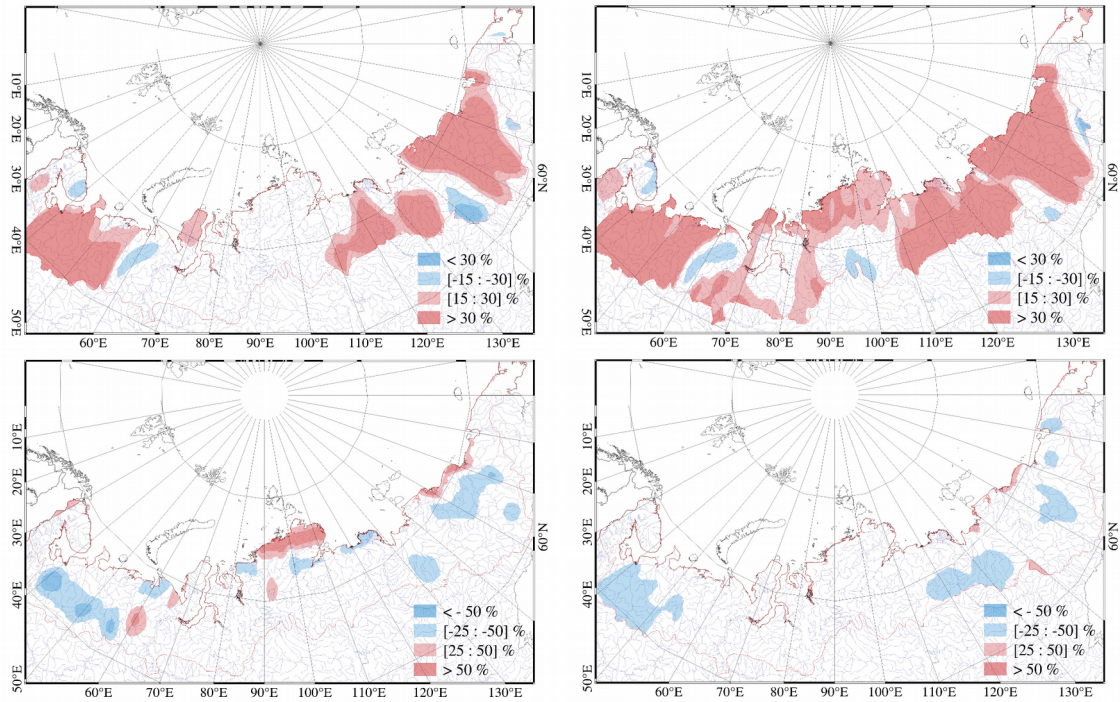



Figure 7. The regions with substantial changes in the mean values (top) and coefficients of variation (bottom) of the spring flood depth of runoff according to the MPIM:ECHAM5 under the SRES:B1 (left) scenario and the MPI-ESM-LR under the RCP 2.6 scenario (right).

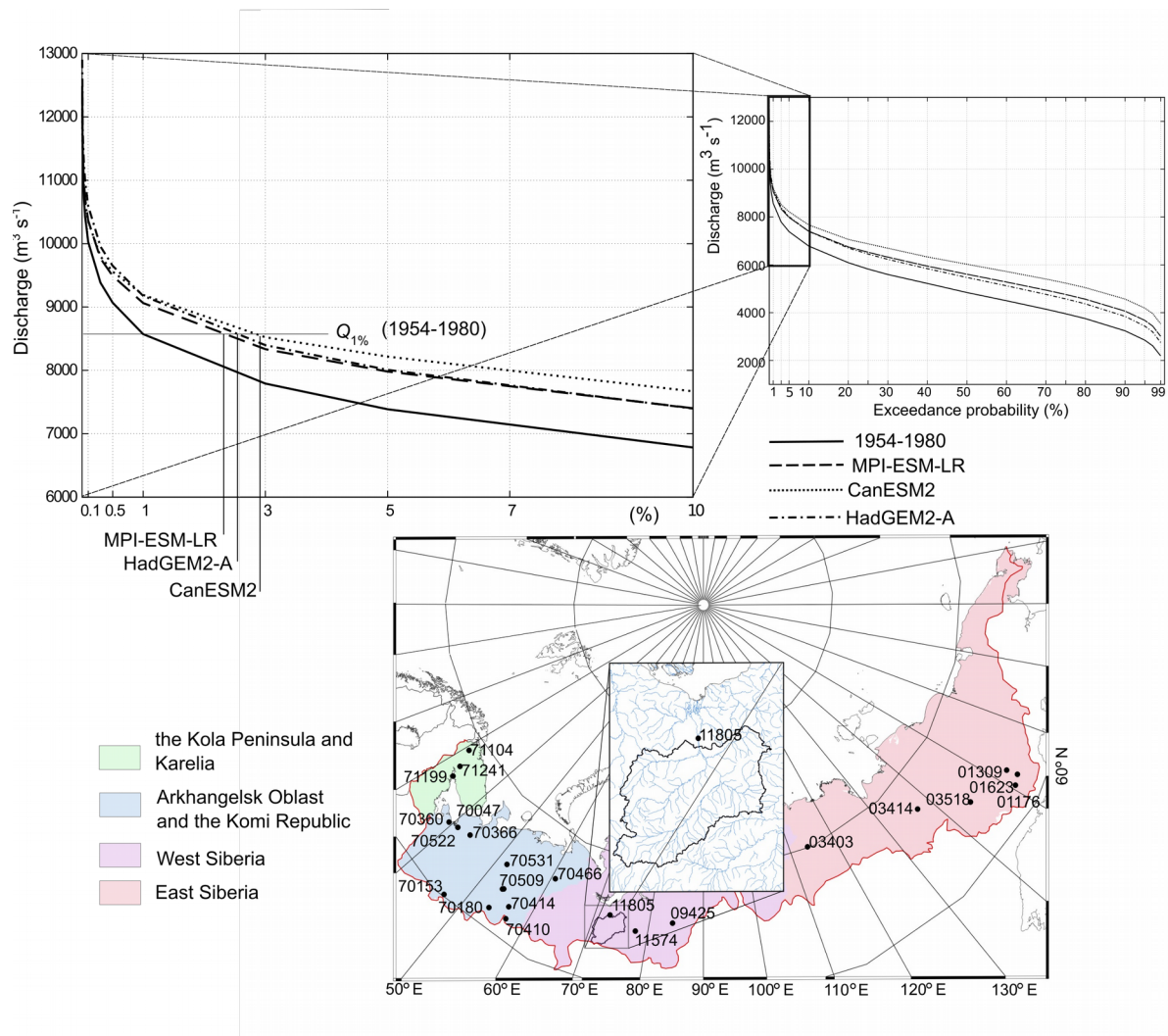



Figure 8. Top: the exceedance probability curves of the peak-flow discharge for the period 1954–1980 and for the projected period 2010–2039 under the RCP 2.6 scenario for the Nadym River at Nadym City (11805). Bottom: the considered regions of the Russian Arctic, the watershed of the Nadym River and location of the gauges used for the model cross-validation.