Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2015-504, 2016
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Published: 15 January 2016

Hydrology and Earth System Sciences
Discussions
Open Access

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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Received: 18 November 2015 – Accepted: 9 December 2015 – Published: 15 January 2016

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Climate warming has been and is expected to continue faster in the Arctic than at lower latitudes, which generates major challenges for adaptation. Among others, long-term planning of development of socio-economic infrastructure requires climate-based forecasts of the frequency and magnitude of extreme flood events. To estimate the cost of facilities and operational risks, a probabilistic form of long-term forecasting is preferable. A stochastic model allowing to simulate the probability density function (PDF) 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 PDFs using historical time series. The PDF parameters of spring flood runoff are assessed in a regional scale under the SRES and RCP climate scenarios 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 runoff are expected. Territories are outlined where 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 calculated.

1 Introduction

The economic importance of the Arctic is an increasingly recognized issue, and various national projects have been initiated 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, and pipelines, and to estimate the costs and flood-related risks during their 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 flow. The PDFs are usually constructed with three parametric distributions (e.g. Pearson's III type) 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 planning horizon (Thomas, 1985). However, the frequency and magnitude of extreme flood events based on historical data do not provide correct estimations for a future under changing climate (Milly et al., 2008).

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 increase in rain, an 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, also the net precipitation (precipitation minus evapotranspiration) is projected to increases during winter. The projected changes discussed above are likely with a high confidence (Collins et al., 2013), and therefore generate an urgent need 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 first one is based on a combined use of regional climate model (RCM) projections and physically-based hydrological models. 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 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 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). Also the large-scale rainfall-runoff models have 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 this studies that the resulting flood frequency estimations are sensitive to the algorithms of the calculation a pseudo-daily precipitation input from projected climatology provided by GCMs (Verzano, 2009). In general, to assess future extreme flood events, one should run the hydrological models for a set of watersheds. Such simulations are, however, computationally expensive, in particular if a multi-model ensemble forcing is used.

The second approach to evaluate the hydrological response to the expected climate change is stochastic. Accordingly, there is no need to generate synthetic time series with a high temporal resolution. This approach considers time series of climate and hydrological variables as realizations of the Markov random process described statistically with a PDF. It is an alternative to physically-based rainfall-runoff modelling, but also contains a physical core. Physical processes on a watershed are depicted through a lumped hydrological model with stochastic components (Domínguez and Rivera, 2010). A stochastic model directly simulates future parameters of multi-year runoff PDFs based on the projected statistics of meteorological variables. Future values of hydrological detrimental extreme events (flood or drought) with required probability of exceedance are assessed by the simulated PDF. For a regional-scale assessment of extreme flood events, calculations are also needed for a set of individual watersheds, but these are computationally much cheaper than in the case of physically-based models. This allows regional estimates for broad territories, as only three parameters of PDF are predicted using the projected statistics of meteorological variables.

The stochastic approach was first proposed by Kovalenko (1993) and Kovalenko et al. (2010) simplified the basic stochastic model for applications of hydrological engineering. 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 and the future. The climate projections are represented as multi-year means of meteorological values for the period of 20–30 years (IPCC, 2007), also based on the quasi-stationarity assumption. Viktorova and Gromova (2010) applied the approach to produce a regional-scale assessment of the future drought extremes for the European part of Russia. Stochastic modelling provides an affordable way to produce probabilistic forecasts of 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. Further, the stochastic 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 for northern territories. It could also be applied to other domains, 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 (see Fig. 3 for the boundary of the region). 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, and the territories are outlined where the frequency and magnitude of the detrimental floods are projected to change substantially. These maps include an alarm for the regions where the engineering calculations of the extreme discharges should be corrected to account for the climate change. 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

In northern regions, a peak flow is formed by snow melting and represented by a spring flood depth of runoff (h, mm), calculated as the volume of flow (m^3) from the drainage basin divided by its area (m^2). This value allows mapping a spatial distribution of a river maximal flow over broad areas due to depiction of a surface runoff independently of the watershed area. The extreme river discharge (Q) with a required probability of exceedance (p) is calculated according to SP 33-101-2003 (2004):

$$Q_\mathrm{p} = k_0 \mu h_\mathrm{p} \delta \delta_1 \delta_2 F / (F + b)^n, \quad (1)$$

where k_0 is a flood coincidence factor, h_p is a spring flood depth of runoff 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; δ, δ_1, δ_2 are watershed fractions of lake, forest and swamp correspondingly, F is a watershed area (km^2) and b and n are factor and degree of a runoff reduction. The values of μ, δ, δ_1, δ_2, b and n may be obtained from look-up tables (SP 33-101-2003, 2004) or from global datasets representing land cover (e.g. Bertholomeé 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 historical 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 stochastic hydrological model is a linear differential equation with stochastic components with solutions statistically equivalent to solutions of the Fokker–Planck–Kolmogorov (FPK) equation (see details in Appendix); it allows evaluating the probability density function of a random hydrological variable with parameters depending on climate variables (Kovalenko, 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 (Kovalenko, 2014; Shevnina, 2014) and to construct the PDFs with theoretical distributions (e.g. Pearson's III types). 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:

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

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; $\overline{c} = 1/k\tau$ is inverse of the runoff coefficient (k) times the watershed reaction delay (τ); $\overline{N}$ (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, calculated using equation $G_{\tilde{N}} = 2(\overline{c}\,m_2 - \overline{N}\,m_1)$.

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

i. To estimate the statistical moments from the historical hydrological and meteorological time series for the chosen reference period ($m_{1\mathrm{r}}$, $m_{2\mathrm{r}}$ and $\overline{N}_\mathrm{r}$).

ii. To assess the model parameters for the reference period: $\overline{c}_\mathrm{r} = \overline{N}_\mathrm{r}/m_{1\mathrm{r}}$ and

$$G_{\tilde{N}\mathrm{r}} = 2\left(\overline{c}_\mathrm{r}m_{2\mathrm{r}} - \overline{N}_\mathrm{r}m_{1\mathrm{r}}\right). \tag{3}$$

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂◂ ▸▸
◂ ▸
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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 ($\overline{N}_\mathrm{f}$), provided that the future parameter values ($\overline{c}_\mathrm{f}$ and $G_{\tilde{N}\mathrm{f}}$) are known:

$$m_{1\mathrm{f}} = \overline{N}_\mathrm{f}/\overline{c}_\mathrm{f} \text{ and } m_{2\mathrm{f}} = \left(2\overline{N}_\mathrm{f} m_{1\mathrm{f}} + G_{\tilde{N}\mathrm{f}}\right)/2\overline{c}_\mathrm{f}. \qquad (4)$$

The values of the parameters $\overline{c}$ 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 versions of handling these parameters are considered.

iv. To obtain the future statistical values of the spring flood depth of runoff: the mean value $\overline{Q}_\mathrm{f} = m_{1\mathrm{f}}$ and the coefficient of variation $C_{\mathrm{vf}} = \sqrt{(m_{2\mathrm{f}} - m_{1\mathrm{f}}^2)}/m_{1\mathrm{f}}$. The future coefficient of skewness (C_{sf}) was calculated from the given ratio of $C_\mathrm{s}/C_\mathrm{v}$ which is considered to be constant for the reference and future periods. The future PDFs were constructed with Pearson's III type 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 to simulate the statistical moments of the multi-year maximal runoff to model PDFs without producing time series. Thus, another procedure, namely cross-validation, was performed to evaluate the model efficiency. 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 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 equals to the size of the total sample (N) minus the chosen minimum ($[N-15]$ in Fig. 1) in this case. Then, the size of the first subsample was incremented by iterator $i = 1, 2, 3 \ldots$ until the size of the second subsample equals 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 with the value of t test exceeding the critical one with 0.05 level of statistical significance. The Student's test critical values with correction to the asymmetry and autocorrelation in hydrological time series were used (Rogdestvenskiy and Saharyuk, 1981). If several partitioning years were recognized, we preferred the year which divided the time series into two approximately equal sub-periods.

For each sub-periods the first and second statistical moments of the spring flood flow depth of runoff 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. For each sub-period, the mean values of the annual precipitation and air temperature were also calculated (Table 1). 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 ($\overline{T}^\text{I}$, $\overline{T}^\text{II}$) and annual precipitation ($\overline{N}^\text{I}$, $\overline{N}^\text{II}$).

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 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 spring flood depth of runoff PDFs were constructed with Pearson's III type 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 by Pearson chi-squared and Kolmogorov-Smirnov one-sample tests. If the value of the test did not exceed the critical of 0.05 level of statistical significance, the case of nominal prediction of the statistical moments was considered to be successful. The model's prediction scores were estimated as percentage of matching PDFs estimated from whole dataset (Table 1).

The example of cross-validation is given for the Yana River at the Verkhoyansk gauge (Fig. 1). To partition of the spring flood depth of runoff time series into two sub-periods: first, the time series (Fig. 1, top panel) was 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 1-year incrementing. At the point $A = 1965$ (Fig. 1, bottom panel), the t test value exceeds the critical of 0.05 level of the statistical significance. Thus, two periods were found: the first sub-period, covering the interval 1935–1964 with $m_1^{\mathrm{I}} = 41.2$ (mm) and the second sub-period covering the interval 1965–2002 with $m_1^{\mathrm{II}} = 52.3$ (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 ($\overline{N}^{\mathrm{I}}$, $\overline{N}^{\mathrm{II}}$) and the annual average air temperature ($\overline{T}^{\mathrm{I}}$, $\overline{T}^{\mathrm{II}}$) were also calculated for two sub-periods. The reference values of the parameters ($\overline{c}_{\mathrm{r}}$, $G_{\tilde{N}\mathrm{r}}$) were estimated using $m_{1\mathrm{r}}^{\mathrm{I}}$, $m_{2\mathrm{r}}^{\mathrm{I}}$ and $\overline{N}_{\mathrm{r}}^{\mathrm{I}}$ for the sub-period 1935–1964 (training). Then, the nominally predicted or modelled $m_{1\mathrm{f}}^{\mathrm{II}}$, $m_{2\mathrm{f}}^{II}$ were calculated from $\overline{N}_{\mathrm{f}}^{\mathrm{II}}$ for the sub-period 1965–2002 (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 $C_{\mathrm{s}}/C_{\mathrm{v}}$ for each period. These values were used to construct the nominally predicted PDFs (or exceedance probability curves – Fig. 2) with a theoretical distribution of the Pearson's III type. Then, the nominally predicted PDFs and empirical PDF were compared (Fig. 2) 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 (control). For the Yana River, only the case of using the regional parameterization by Shevnina (2012) for the sub-period 1965–2002 was successful.

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 (1000–50 000 km^2) were used. The gauges are located on the territory of the Russian Arctic (see Fig. 6 for the regional boundary). The gauging sites are irregularly distributed over the territory with 65 % of the points located at the European part of Arctic. The time series lengths vary from 26 to 77 years with average of 51 years. The time series with the observations longer then 50 years are available for 30 % of the sites. The dataset has no gaps in 66 % cases and in 18 % of cases contain the missing values for more then 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, Fig. 6) which is 30 % of the considered data. For the corresponded 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 a watershed) for each sub-period (Table 1). The historical time series of the annual precipitation amount and the average air temperature for the meteorological sites were obtained from Razuvaev et al. (1993), the archive of Arctic and Antarctic Research Institute (N. Bryazgin, personal communication, 2008) 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 versions of the parameters setting (Table 2). Also, the statistical moments were considered to be constant during the entire observed period. In this case, the nominally predicted PDF for the one sub-period was modelled using the statistical values calculated from observed data of the other sub-period (“no model” case). For each version of the nominal prediction, the percentage of the successful PDFs’ matching was obtained (Table 3) using the Pearson chi-squared and Kolmogorov-Smirnov one-sampled tests.

The model with the constant parameters gives better result then the case of no model: the percentage of the successful nominal predictions is over 5–10 % higher (Table 3). Using the regional parameterization algorithm to calculate the parameter $\overline{c}$ gives the advantage of over 11–22 % in the percentage of the successful nominally predicted PDFs. Hereinafter, we used regional-oriented parameterization scheme to estimate the future statistical moments of the spring flood flow depth of runoff using the climate change projections.

2.3 Data and method application

Climate models provide more than 20 projections for several scenarios of future climate (IPCC, 2007; Taylor et al., 2012). In this study, the model results for two SRES (A1B and B1) and two RCP (2.6 and 4.5) scenarios were used to estimate the statistics of spring flood depth of runoff (the mean, the coefficient of variation and coefficient of skewness). Results of climate models developed by the Max Planck Institute for Meteorology (MPIM:ECHAM5, MPI-ESM-LS), Hadley Center for Climate Prediction and Research (UKMO:HADCM3, HadGEM2-A), Geophysical Fluid Dynamics Laboratory (GFDL:CM2) and Canadian Center for Climate Modelling and Analysis (CaESM2) were used. 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. 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. The reference climatology was obtained from the catalogues of climatology and the archive of the Arctic and Antarctic Research Institute for 209 meteorological stations located in the Russian Arctic. The climatology was interpolated into the model grid nodes using the algorithm by Hofierka et al. (2002).

The values of $\overline{c}$ 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 depth of runoff were calculated according to Eq. (4) using projected climatology. The coefficients of skewness were estimated using the regional ratio of $C_\mathrm{s}/C_\mathrm{v}$. The maximum discharge with the required exceedance probability was calculated according to Eq. (1) using the projected PDFs of the spring flood depth of runoff constructed based on the projected mean value, the coefficient of variation and coefficient of skewness (see Sect. 3 for an example). Our study was performed for the period 2010–2039 since within this time interval the actual and developing socio-economic infrastructure (bridges, oil/gas pipelines, roads and dams) will operate.

Regions with substantial changes in the mean values and the coefficients of variation of the spring flood flow depth were outlined. For these regions, the flood extreme maximum discharges should be corrected according to the climate change when used to design the hydraulic constructions and to estimate the risks during their operation. The changes are considered to be substantial if they differ from the reference values for more than 15/25 % for the mean values/the coefficients of variation (Kovalenko, 1993). These thresholds reflect the general uncertainties which depend not only on the hydro-

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

logical data accuracy, but also on the biases of the climate projections used to force the stochastic model.

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). 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 6 % and warming of over 2.1 °C are predicted according to the SRES scenarios. For the RCP scenarios, the changes of climatology are more pronounced, and the precipitation mean values are expected to increase by more than 12 % and to be accompanied with a warming of 3.3 °C. The strongest increase (over 16 %) in precipitations with the highest warming (over 3.9 °C) is predicted by CaESM2 for the RCP2.6 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 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 depth of runoff are more notable: based on the RCP2.6 scenario, an increase of over 23 % in the mean values and a decrease of over 16 % in the coefficients of variation are expected. The strongest increase (over 27 %) of the mean values with a lowest decrease of the coefficients of variation (over 17 %) is predicted by CaESM2 for the RCP2.6 scenario.

According to all scenarios considered, the highest increase of the future mean values of spring flood depth of runoff (of 30–35 %) is expected for the European part of the Arctic (Fig. 3). Moderate changes in the mean values (of 10–18 %) are also predicted for Siberia mostly according to the RCP scenarios. For the SRES scenarios, an increase of 10–18 % in the mean values is predicted for the northern European Arctic, accompanied by a decrease of the coefficients of variation.

It is very difficult to compare our result with other studies because different flood characteristics are addressed. Only indirect comparison is possible assuming that, for Pearson III distributions an increase of means even together with a decrease of coefficients of variation leads to an increase of upper-tail runoff values. Then, today's 100-years' flood would occur more frequently in the future (Fig. 4). Also, a decrease of means even together with a slight increase of coefficients of variation leads to a decrease of upper-tail runoff values. In this case, we can expect 100-years' flood values would decrease compare with historical values. 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 of historical 100-years maximum discharges was predicted by Hirabayashi et al. (2008, 2013) under the SRES:A1B scenario for the period 2001–2030, which is in accordance with our results. However, for the northeastern European Arctic we expect a significant increase the frequency of today's 100-years flood events in contrast to Hirabayashi et al. (2013). The feasible reason of such disagreement is the spatial coarseness of the model calibrated using the observations from the watersheds larger than 100 000 km^2. In our study, the stochastic model was calibrated using the observations for watersheds of the 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 today's 100-years 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 today's 100-years flood for north-eastern Europe (i.e. Finland, northern Russia and part of the Baltic

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

States) under the SRES:A2 and SRES:B2 scenarios, which is in general agreement with our results. A similar decreasing tendency of the projected maximal discharges was obtained by Veijalainen et al. (2010) for the northern Finland using the physically-based model.

Figure 5 represents the regions with the 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 the detrimental floods are expected to change substantially from the historical 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 RCP2.6 scenario. A substantial increase in the mean values is expected for the most of the European Arctic and Eastern Siberia. In these regions, the calculations of the spring flood maximum discharges should be corrected according to the expected climate change. The example of the climate-based correction for the Nadym River watershed according to climate model outputs for the RCP2.6 scenario is given below.

The new bridge over the Nadym River (gauge number 11805 in the bottom panel of Fig. 6) is planned to be build according to the Strategy (2013). The bridge height (and cost) assessment require the maximum discharge of rare occurrence (e.g. with a probability of exceedance of 1 %). The watershed of the Nadym River is located on the south part of the Western Siberia, where an increase of over 15–30 % in the mean values of the spring flood flow depth is predicted under the scenarios considered. Thus, the climate-changed upper-tail maximum discharge will larger than the historical value.

Hydrological observations for the Nadym River are available at the Nadym city gauge (the watershed area is 48 000 km^2). For this gauge, for the period 1950–1980 the statistical values of the spring flood depth of runoff were calculated from the observations (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 RCP2.6 scenario was obtained from CMIP5 dataset. The parameter $G_{\tilde{N}}$ was estimated according to the observed climatology and the parameter $\overline{c}$ was calculated based on the projected climatology. These values were used to calculate the projected first and second statistical moments (m_1 and m_2) of the spring flood flow depth of runoff. The projected coefficient of variation was estimated by equation $C_\mathrm{v} = \sqrt{(m_2 - m_1^2)}/m_1$. The projected coefficient of skewness was obtained from the ratio of $C_\mathrm{s}/C_\mathrm{v}$ using the projected coefficient of variation. The projected PDF was constructed using these values with Pearson's III type 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 % ($Q_{1\%}$, $\mathrm{m^3\,s^{-1}}$) was estimated from $h_{1\%}$ according to Eq. (1).

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

4 Conclusions

A stochastic model was applied in estimating the impact of the climate change on the frequency and magnitude of extreme flood events in the Russian Arctic. The stochastic model allows calculating the future extreme floods 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's III type theoretical distribution. The projected frequency and magnitude of extreme flood events with a required probability of exceedance were then extracted from the simulated PDFs.

The stochastic model was further applied for a regional-scale assessment of extreme flood events for the Russian Arctic. The advanced model parameterization by Shevnina (2012) allows to successfully predicting 67–83 % of the PDFs (see Sect. 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, RCP2.6 and RCP4.5 climate scenarios with outputs of three climate models. For the region studied, an increase of 17–23 % in the spring flood depth of runoff mean values 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 of 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 outlined for 2010–2039. For the territories where the mean values and coefficients of variation increased a lot, the extreme flood events will occur more frequently. For such alarm regions, 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 the hydraulic constructions, oil-gas industry, transport infrastructure and population.

The stochastic model 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 the low number of simulated variables and parameters. Also, the regionally-oriented parameterization is 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 stochastic 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 the climate change, especially for regions with a lack of sufficient observations. It could be useful for a broad-scale assessment to define alarm regions, where an essential increase/decrease of the extremal flood events are expected. When the alarm 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 stochastic and rainfall-runoff models is of a high interest.

Another weakness 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 stochastic model to estimate the frequency/magnitude of extreme floods for watersheds of different size.

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

Appendix A

The concept of stochastic modelling to perform a hydrological response on an expected climate change was proposed by Kovalenko (1993), it is presented further follow to 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 Markov chain (Rogdestvenskiy, 1988). Then, a first order ordinary differential equation is used as lump hydrological model to perform multi-year flow time series:

$$\mathrm{d}Q/\mathrm{d}t = (1k\tau)Q + \dot{X}/\tau \tag{A1}$$

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 the watershed reaction to the incoming precipitation (here, $\tau = 1$ 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 ($\tilde{c}$, $\tilde{N}$ are performed as "white noise") to $c = \overline{c} + \tilde{c}$ and $N = \overline{N} + \tilde{N}$ we obtain the stochastic differential equation:

$$\mathrm{d}Q = [-(\overline{c} + \tilde{c})Q + (\overline{N} + \tilde{N})]\mathrm{d}t. \tag{A2}$$

The random components are mutually correlated.

The solution of Eq. (A2) is statistically equivalent to the solution of the Fokker–Planck–Kolmogorov (FPK) equation (Domínguez and Rivera, 2014):

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

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:

$$\begin{aligned} A(Q;t) &= -\left(\overline{c} + 0.5G_{\overline{c}}\right)Q - 0.5G_{\tilde{c}\tilde{N}} + \overline{N}; \\ B(Q;t) &= G_{\overline{c}}Q^2 - 2G_{\tilde{c}\tilde{N}} + G_{\tilde{N}}, \end{aligned} \tag{A4}$$

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 $G_{\tilde{N}}$.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀▮ | ▮▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

In engineering hydrological application 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 ($i = 1, 2, 3$):

$$
\begin{aligned}
\mathrm{d}m_1/\mathrm{d}t &= -\left(\overline{c} - 0.5G_{\tilde{c}}\right) m_1 - 0.5G_{\tilde{c}\tilde{N}} + \overline{N};\\
\mathrm{d}m_2/\mathrm{d}t &= -2\left(\overline{c} - G_{\tilde{c}}\right) m_2 + 2\overline{N}m_1 - 3G_{\tilde{c}\tilde{N}}m_1 + G_{\tilde{N}};\\
\mathrm{d}m_3/\mathrm{d}t &= -3\left(\overline{c} - 1.5G_{\tilde{c}}\right) m_3 + 3\overline{N}m_2 - 7.5G_{\tilde{c}\tilde{N}}m_2 + 3G_{\tilde{N}}m_1.
\end{aligned}
\tag{A5}
$$

This system allows to calculate the statistics of the multi-year runoff: the mean $\overline{Q} = f(m_1)$, the coefficient of variation $C_\mathrm{v} = f(m_1, m_2)$ and the coefficient of skewness $C_\mathrm{s} = f(m_1, m_2, m_3$. Further, the constant value of $C_\mathrm{s}/C_\mathrm{v}$ ratio for the projected time period was used to simplify the Eq. (A5), it is commonly apply 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 climate changes within an assumption of "quasi-stationarity" and this may be also applied for the hydrological regime. This allows further simplifications of Eq. (A5): $\mathrm{d}m_i/\mathrm{d}t \approx 0$ 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:

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

This system may be applied to estimate the multi-year hydrological statistical moments directly from climatology for each "quasi-stationary" time period (e.g. 2010–2039).

Acknowledgements. This study was funded through the Ministry of Education and Science of the Russian Federation (project 1413) and supported by the Academy of Finland (contract 283101).

HESSD

doi:10.5194/hess-2015-504

Extreme flood events in changing climate for a long-term planning (Russian Arctic)

E. Shevnina et al.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

References

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Table 1. The multi-year statistical values of the spring flood depth of runoff and the climatology for the sub-periods with the statistically significant shift in the mean values (for denotations see the text).

Gauge ID	River	Catchment area [km^2]	Period	m_1 [mm]	m_2 [mm^2]	C_v	C_s/C_v	$\overline{N}$ [mm]	$\overline{T}$ [°C]
01176	Bohapcha	13 600	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	45 300	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	10 100	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	31 400	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	48 000	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	15 200	1931–1946	126	16 716	0.23	2.0	575	1.6
			1947–1980	144	22 994	0.33	1.4	591	1.6

Table 1. Continued.

Gauge ID	River	Catchment area [km^2]	Period	m_1 [mm]	m_2 [mm^2]	C_v	C_s/C_v	$\overline{N}$ [mm]	$\overline{T}$ [°C]
70180	Vychegda	26 500	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	29 400	1938–1956	250	65 806	0.23	0.5	490	−1.0
			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	15 000	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

Table 2. The parameters $G_{\tilde{N}}$ and $\overline{c}$ (for explanation see the text) and the nominally predicted multi-year statistical moments of the spring flood depth of runoff for the different catchments located in the Russian Arctic.

Gauge ID	Lat/lon	Period	$G_{\tilde{N}}$ [mm^2]	$\overline{c}$	m_{1f} [mm]	m_{2f} [mm^2]	C_{vf}	C_{sf}
01176	62°06′ N/	1934–1949	23 366	3.79	115	16 234	0.48	1.20
	150°37′ E	1950–1980	24 841	3.09	136	22 647	0.46	1.28
01309	63°17′ N/	1941–1956	18 370	1.96	155	28 815	0.44	1.38
	152°02′ E	1957–1977	4635	1.94	141	20 941	0.25	1.26
01623	62°22′ N/	1935–1950	18 208	2.88	150	25 584	0.38	1.50
	152°20′ E	1951–1980	17 936	2.39	178	35 398	0.34	1.54
03403	70°11′ N/	1943–1985	6477	2.60	101	11 383	0.35	0.27
	113°57′ E	1986–2002	3799	2.26	113	13 587	0.26	0.29
03414	67°24′ N/	1935–1964	4390	4.32	42.0	2209	0.55	0.68
	137°15′ E	1965–2002	4347	3.36	52.7	3425	0.48	0.68
03518	64°43′ N/	1944–1985	6436	3.39	66.0	5243	0.47	0.38
	144°37′ E	1986–2002	5167	2.61	86.9	8543	0.36	0.36
09425	65°58′ N/	1941–1970	10 047	2.12	233	56 857	0.21	0.27
	84°17′ E	1971–1999	10 275	1.90	258	69 485	0.20	0.27
11574	64°56′ N/	1954–1970	6625	3.39	151	23 906	0.21	0.86
	77°48′ E	1971–2001	10 408	3.17	152	24 718	0.27	0.27
11805	65°39′ N/	1955–1974	8398	3.02	156	25 636	0.24	0.72
	72°42′ E	1975–1991	13 505	3.36	146	23 220	0.31	0.66
70047	64°41′ N/	1928–1958	12 469	2.76	200	42 164	0.24	0.21
	39°32′ E	1959–1980	14 391	3.56	147	23 753	0.30	0.23

Table 2. Continued.

Gauge ID	Lat/lon	Period	$G_{\tilde{N}}$ [mm^2]	$\bar{c}$	m_{1f} [mm]	m_{2f} [mm^2]	C_{vf}	C_{sf}
70153	60°12′ N/	1931–1946	7665	4.56	130	17 612	0.22	0.46
	47°00′ E	1947–1980	18 536	4.10	140	21 886	0.34	0.48
70 180	61°52′ N/	1930–1956	9022	3.34	165	28 465	0.22	−0.01
	53°49′ E	1957–1980	11 481	3.29	149	23 969	0.28	−0.01
70360	64°25′ N/	1939–1958	25 423	2.43	224	55 552	0.32	0.38
	41°03′ E	1959–1977	14 897	3.14	170	31 225	0.29	0.40
70366	64°59′ N/	1927–1958	18 073	3.49	128	18 970	0.40	0.55
	43°42′ E	1959–1980	12 020	4.05	115	14 749	0.33	0.51
70410	61°52′ N/	1914–1930	10 098	1.71	330	111 916	0.16	−0.06
	56°57′ E	1931–1993	13 730	2.04	253	67 121	0.23	−0.08
70414	62°57′ N/	1938–1956	12 960	1.96	307	97 330	0.19	0.10
	56°56′ E	1957–1980	8554	2.16	227	53351	0.20	0.15
70466	66°36′ N/	1936–1957	18 000	1.25	445	205 006	0.19	0.29
	60°52′ E	1958–1980	15 331	1.32	367	140 521	0.21	0.38
70509	63°49′ N/	1933–1949	10 124	2.46	217	49 166	0.21	0.03
	53°58′ E	1950–1980	8271	3.34	139	20 651	0.25	0.03
70522	63°35′ N/	1934–1949	10 051	2.78	192	38 779	0.22	0.19
	53°51′ E	1950–1980	9630	3.72	127	17 504	0.28	0.25
70531	65°17′ N/	1937–1964	10 545	3.77	147	22 867	0.26	0.23
	51°55′ E	1965–1980	12 983	3.68	132	10 205	0.32	0.30

Table 2. Continued.

Gauge ID	Lat/lon	Period	$G_{\tilde{N}}$ [mm^2]	$\overline{c}$	$m_{1\mathrm{f}}$ [mm]	$m_{2\mathrm{f}}$ [mm^2]	C_{vf}	C_{sf}
71104	68°56′ N/	1928–1958	9287	1.92	239	59 383	0.21	0.13
	30°55′ E	1959–1994	11 647	2.26	155	26 536	0.33	0.85
71199	66°52′ N/	1931–1958	10 865	2.30	207	45 013	0.24	0.15
	33°20′ E	1959–1994	11 098	3.19	130	18 606	0.32	0.24
71241	67°18′ N/	1934–1948	5638	4.51	124	15 878	0.20	0.53
	32°08′ E	1949–1980	12 086	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 the 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 and predicted climatology (2010–2039) and statistical values of the spring flood depth of runoff averaged for the entire territory of the Russian Arctic[*].

Multi-year statistical values	Reference climatology	Fourth Aassessment report (AR4)		Fifth assessment report (AR5)	
		SRES:A1B	SRES:B1	RCP4.5	RCP2.6
The annual amount of precipitation mean value (PRE mm)	378	400	402	424	424
The average annual air temperature mean value (TAS °C)	−10.3	−8.2	−8.2	−6.9	−7.2
The spring flood depth of runoff (SFD) mean value mm	162	189	190	201	199
The spring flood depth of runoff variation coefficient (C_v SFD)	0.30	0.30	0.29	0.29	0.25

[*] as proposed by Ivanov and Yankina (1993).

Table 5. Predicted climatology and statistical values of the spring flood depth of runoff averaged for the entire territory of the Russian Arctic for the period 2010–2039 according to result of different climate models.

Dataset	Scenario	GCM	PRE[*], [mm]	TAS, [°C]	SFD, [mm]	C_v SFD
AR4	SRES:A1B	MPIM:ECHAM5	393	−8.6	184	0.30
		UKMO: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
		UKMO:HadCM3	405	−8.1	191	0.30
		GFDL:CM2	415	−8.2	196	0.28
AR5	RCP4.5	MPI-ESM-LR	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-LR	415	−7.2	197	0.26
		HadGEM2-A	419	−7.9	194	0.26
		CanESM2	438	−6.4	207	0.24

[*] See abbreviation in Table 4.

Table 6. Climatology and the statistical values of flood runoff for the Nadym River at Nadym City for the historical period and the projection for the period 2010–2039 under the RCP2.6 (for denotations, see the text).

Multi-year	Historical	Result according to GCM			
values	period	HadGEM2-A	MPI-ESM-LR	CanESM2	Multi model
$\overline{N}$ mm	431	483	491	519	498
$\overline{T}$ °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
$Q_{1\%}$ $\text{m}^3\,\text{s}^{-1}$	8572	9177	9062	9191	9144

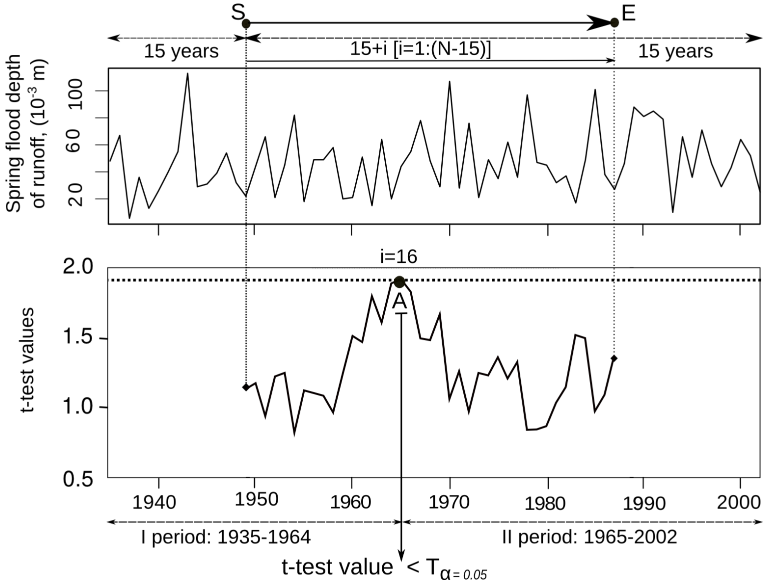

Figure 1. The partition of the observed time series of the spring flood depth of runoff (top panel) into sub-periods with statistically significant shift in the mean value by Student's *t* test (bottom panel) for the Yana River at the Verkhoyansk City gauge: $T_{\alpha=0.05}$ is the critical value of the *t* test at the threshold of the statistical significance equals to 0.05.

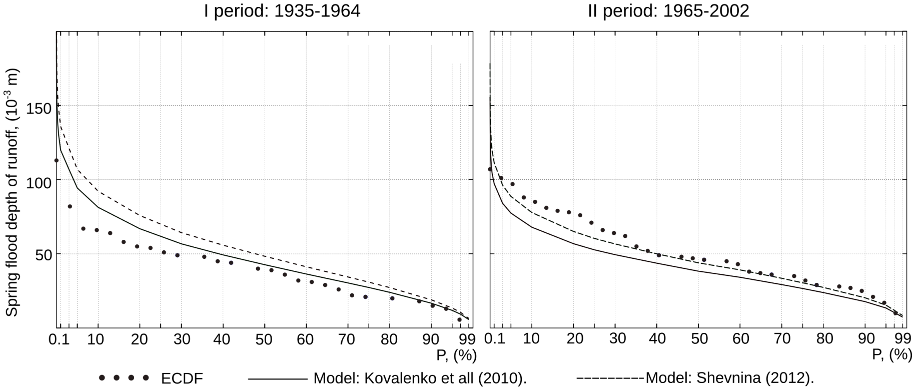

Figure 2. The nominally predicted exceedance probability curves fitted to the empirical data for the sub-periods with statistically significant shift in the mean value: the Yana River at the Verkhoyansk City (ECDF – empirical exceedance probability).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

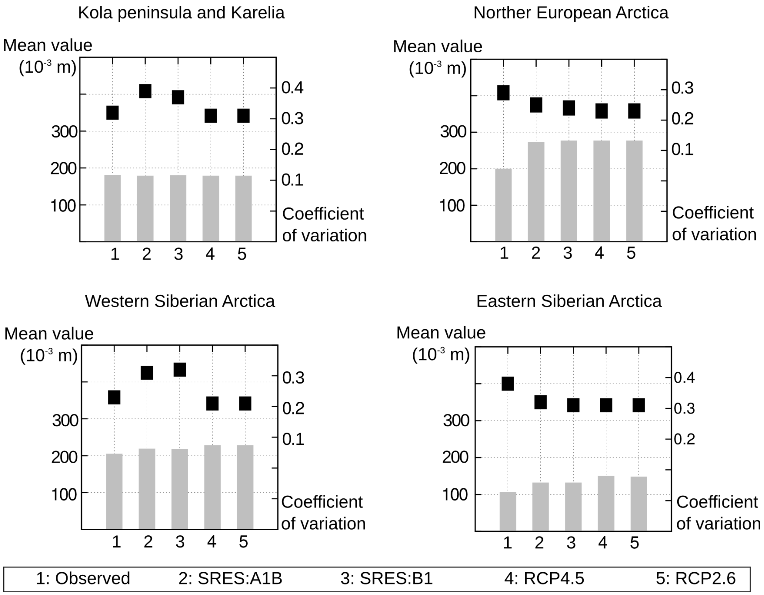

Figure 3. The changes of the mean values (bars) and coefficients of variation (squares) of the spring flood depth of runoff expected for the regions of the Russian Arctic for the period 2010–2039.

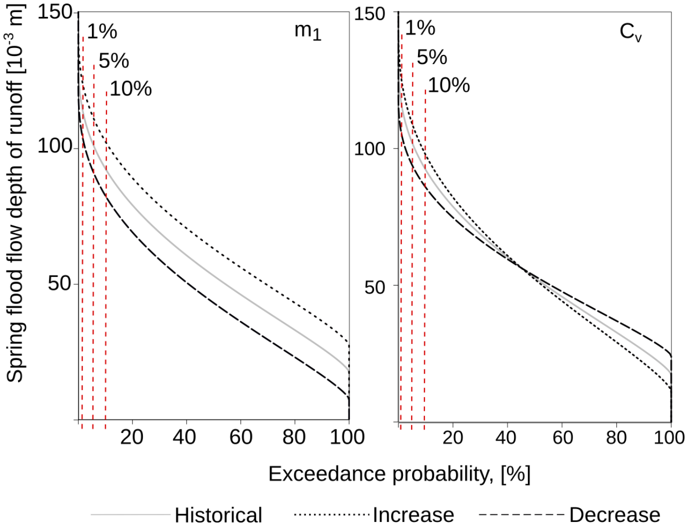

Figure 4. To illustrate the changes in the upper-tail values due to changes in parameters of the PDF (the mean values and coefficient of variation).

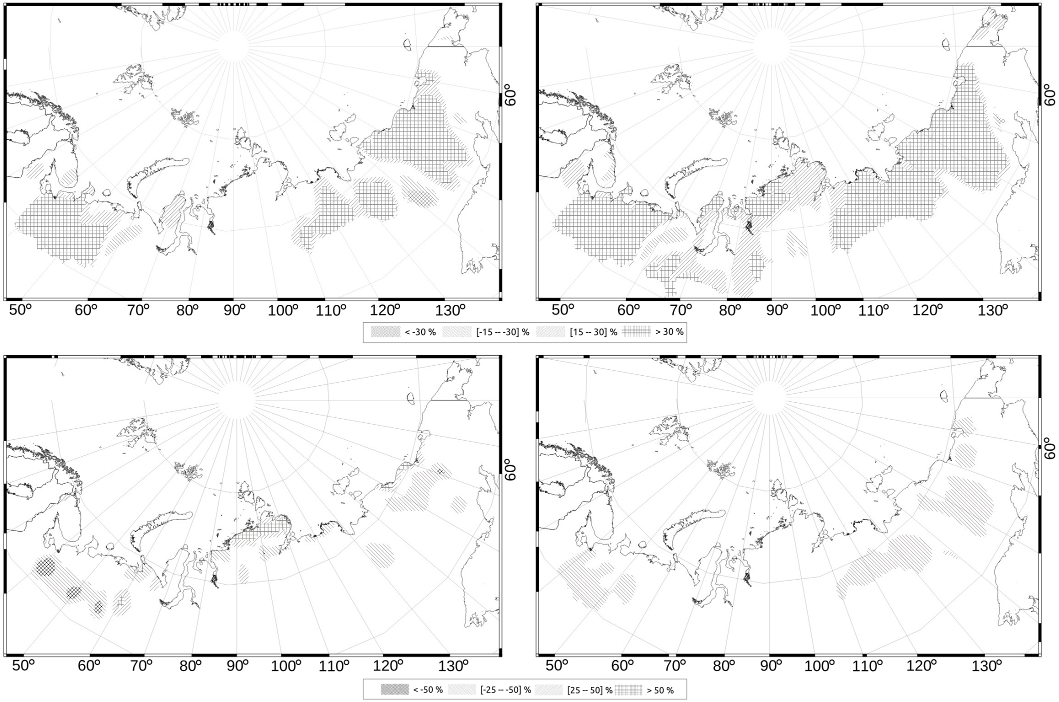

Figure 5. The regions with substantial changes in the mean values (top panels) and coefficients of variation (bottom panels) of the spring flood depth of runoff according to the SRES:B1 MPIM:ECHAM5 (left panels) and the RCP2.6 MPI-ESM-LR (right panels).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
I◀ | ▶I
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

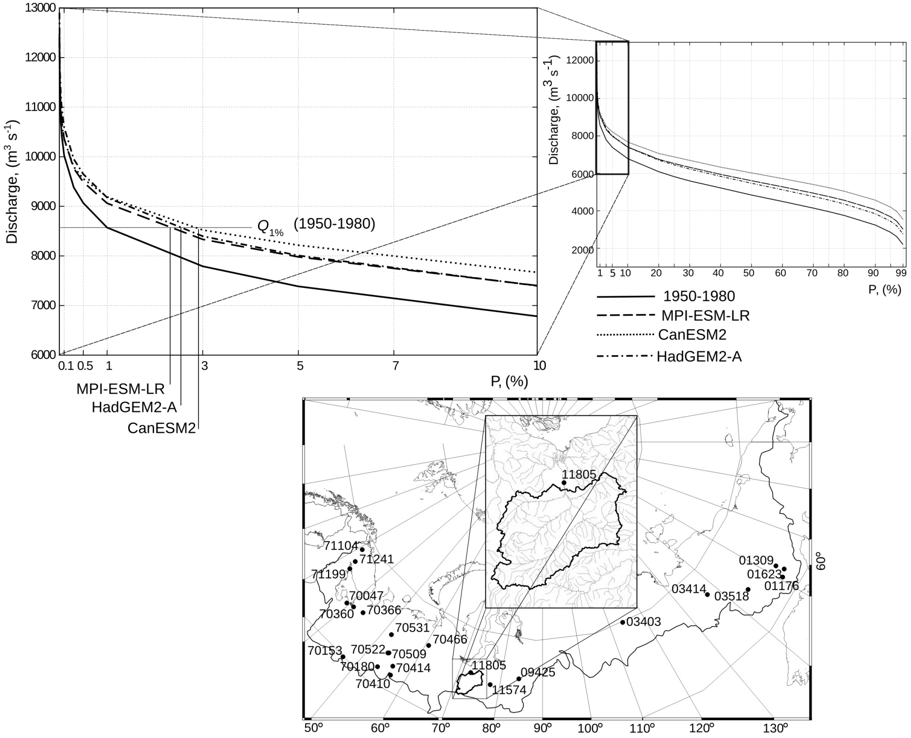

Figure 6. The exceedance probability curves of the peak-flow discharge for the historical period and projection for the period 2010–2039 under the RCP2.6 scenario (top panels) for the Nadym River at the Nadym City (11805): points and numbers correspond to the gauges (bottom panel) used for the model cross-validation – the solid black line outlines the territory of the Russian Arctic according to Ivanov and Yankina (1993).