Assessing runoff sensitivity to climate change in the Arctic basin: empirical and modelling approaches

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Abstract Empirical and modelling approaches to assessing runoff sensitivity to climate change are presented by the example of the large rivers of the Arctic basin. The empirical approach has been carried out for seven large Arctic rivers. It is based on comparing the climatic mean of runoff estimated for the "warm" years of observations with the corresponding mean for the "cold" years. The registered differences in maximum annual runoff estimated for the "warm" and "cold" years have been found statistically insignificant, even under the large (up to 4°C) differences in the observed annual temperature for these years. The differences in minimum annual runoff turned out significant for three of the seven rivers. The modelling approach has been demonstrated on the basis of the ECOMAG modelling system applied for the Lena River (catchment area 2 488 000 km^2). The parameters of the model have been adjusted through calibration against runoff hydrographs observed for the 10-year period 2000–2009. Validation of the model has been performed for the period 1986–1999. The numerical experiments have been carried out to analyse the sensitivity of the Lena River runoff regime to possible changes in annual precipitation and air temperature. It has been shown that one-degree increase of the annual temperature leads to decreasing simulated annual runoff of about 5–7%, mainly due to increasing evaporation. Ten percent increase of precipitation leads to 15–17% increase in simulated annual runoff.

Key words cold region hydrology; climate change; sensitivity

INTRODUCTION

High uncertainty is associated with the assessment of hydrological consequences of observed and projected climate changes. Part of the uncertainty is epistemic, a result of incomplete knowledge of the physical mechanisms of dynamics of climatic systems and interrelations with the hydrological cycle, deficiency of observations, etc., and this can be reduced by deepening knowledge and accumulating data. In addition, structural uncertainty, which cannot be reduced even if detailed information becomes available, is an essential feature of the climatic and hydrologic systems. Structural uncertainty is emphasized by physically-founded limits of predictability of atmospheric processes and unpredictability of the factors (e.g. development of technologies) affecting climate change, as well as by stochastic aspects of climatic and hydrological processes represented as non-static Hurst-Kolmogorov behaviour (Koutsoyiannis, 2003; Montanari, 2003). The relationship between the epistemic and structural uncertainties is a key question for understanding the opportunity for assessment of hydrological consequences of climate change, and there are different views on this relationship (see discussion in Koutsoyiannis *et al*., 2009). Taking into account significant and *a priori* unknown uncertainty of the climate projections, one can suggest that there is a very limited range of the problems (related to response of hydrological systems to climate change), which presume existing meaningful solutions. Assessing runoff sensitivity to climate change is an example of these problems.

Here, empirical (data-based) and physically-based modelling approaches to such assessment are presented by the example for the large rivers (or their tributaries) draining into the Arctic Ocean.

Climate over the Arctic region has changed significantly during the past few decades and climate models predict that the regional warming (2–9°C by the end of the 21st century) is very likely to exceed the global mean warming (Climate Change, 2007). The hydrological cycle of the Arctic river basins plays a central role in regulating the global climate system and investigation of their runoff regime is therefore critical to better understand and quantify the atmosphere-land-ocean interactions in the Arctic and consequent global impacts (Shiklomanov *et al*., 2000; Vörösmarty *et al*., 2001; Yang *et al*., 2004).

The ongoing changes of the Arctic river runoff are estimated differently. For example, according to Bates *et al*. (2008), annual runoff of the six greatest Eurasian rivers has slightly (7%) increased in the 20th century. At the same time, the authors of the report (Climate Change in Russia, 2008) have assessed these changes as “significant” for 1978–2005; e.g. the annual runoff increasing is assessed as 15% in the northeast of Asian Russia. Finally, Shiklomanov (2008) concluded that there are not any significant trends in the annual runoff during the periods of observations in the large rivers of the Arctic basin, such as the Ob’, Yenisei, Lena, Yana, Indigirka and Kolyma.

The assessed changes of winter runoff varied significantly as well. According to *Climate Change* (2007) winter runoff of the Arctic rivers has increased significantly (from 25 to 90%) for the period 1935–1999, while in Shiklomanov (2008) the positive trends in winter runoff have been estimated as statistically insignificant for the periods of observation at the largest Siberian rivers.

It is a complex problem to discriminate by statistical analysis of time-series of hydrological observations, between the trends associated with climate changes on the one hand and with the internal climate variability on the other. First, this complexity results from weakness of the climate change signal compared with the natural variability of climatic system. The second reason is the deficiency of series of hydrological observations and non-homogeneity of these series. One of the consequences of the latter reason is that typically-used statistical methods can give, as shown above, different conclusions on the significance and magnitude of runoff changes. Under these circumstances, opportunities of obtaining reliable estimates can be associated with the suggested empirical approach to analysis of natural runoff sensitivity to climate parameters. In the following section the essence of the approach and the main results of its application are presented.

ASSESSING NATURAL SENSITIVITY OF RUNOFF TO CLIMATE WARMING IN THE ARCTIC BASIN: AN EMPIRICAL ANALYSIS

Over most regions of the Earth, the magnitude of variations of the annual air temperature is much larger than the projected regional changes of the corresponding climatic norm. This fact, given that long-term series of hydrometeorological observations are available, creates a principal opportunity to assess “natural” sensitivity of the observed runoff to changes of the observed annual temperature. We used the word “natural” in order to stress that the assessment is made only on the basis of runoff and temperature observations. The Null hypothesis is formulated as: the registered difference between the observed runoff value (e.g. annual, maximum, minimum, etc.) in “warm” years and the corresponding value in “cold” years is the result of chance, not a real effect. To test this hypothesis, multi-year series of hydrological and meteorological observations in seven Arctic river basins were used: North Dvina, Pechora, Taz, Olenek, Yana, Indigirka and Anadyr (Fig. 1).

Fig. 1 Location of the study basins.

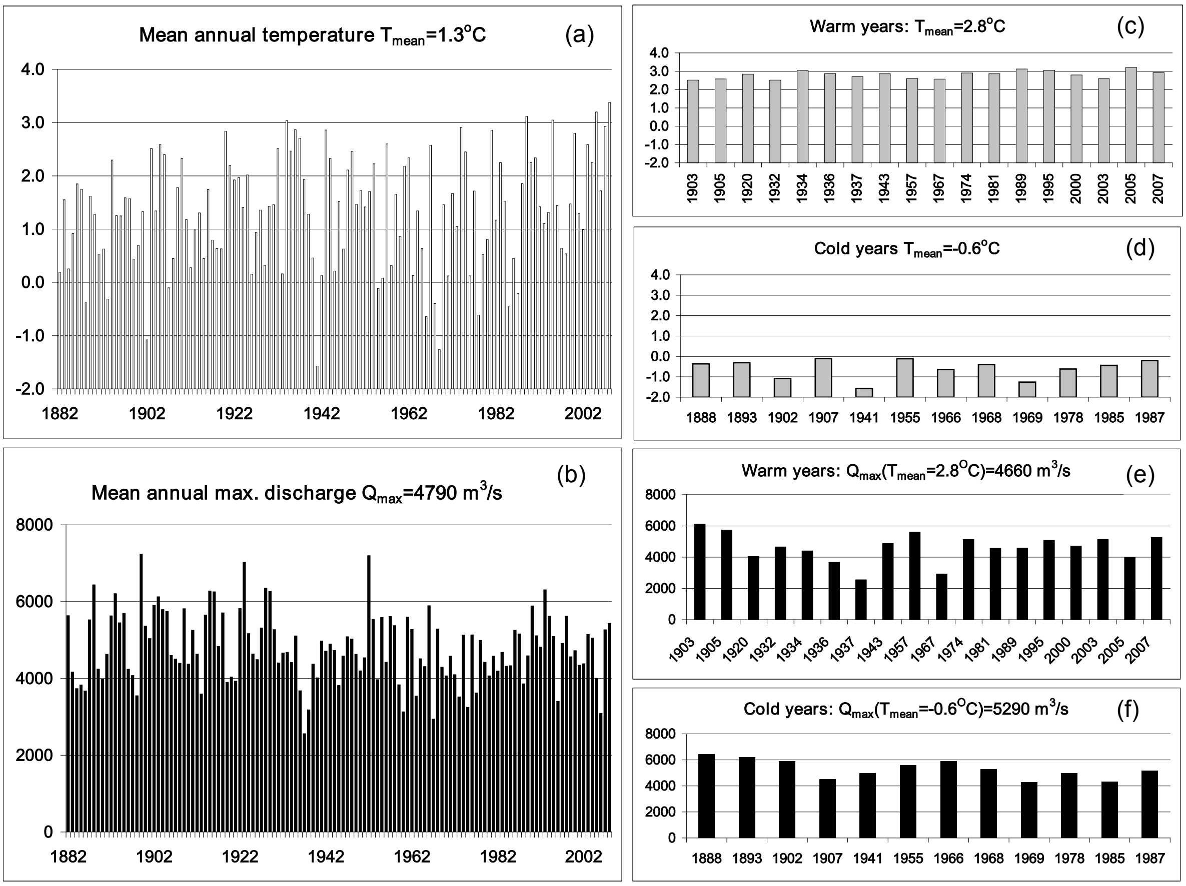

Fig. 2 Illustration of the sampling procedure used (by the example of the Northern Dvina River). (a) Observed mean annual temperature in the river basin; (b) observed maximum monthly discharge; samples of "warm" (c) and "cold" (d) years; samples of maximum monthly discharges observed in the "warm" (e) and "cold" (f) years.

Duration of observations varies from 37 to 127 years. Three data sets were sampled for each basin: (1) values of annual air temperature, T_{mean}, averaged over a basin, (2) annual maximum, Q_{max}, and (3) annual minimum, Q_{min}, of monthly discharge at a basin outlet. The sampled data sets were treated with the help of the following sampling procedure, illustrated in Fig. 2 by the example of the Northern Dvina River data sets.

In order to assess for each of the considered basins sensitivity of maximum runoff to changes of the climatic mean of annual air temperature, several pairs of the censoring samples $Q_{\max}^{warm} = Q_{\max}\left|\left(T_{mean} > \overline{T_{mean}} + \Delta\right)\right.$ and $Q_{\max}^{cold} = Q_{\max}\left|\left(T_{mean} < \overline{T_{mean}} - \Delta\right)\right.$ (Fig. 2(e),(f)) were selected from the time series of T_{mean} and Q_{max} (Fig. 2(a),(b)), where $Q_{\max}^{warm}$ and $Q_{\max}^{cold}$ are the samples of annual maximum discharge in the "warm" and "cold" years, respectively; $\overline{T_{mean}}$ is the climatic mean of annual air temperature; Δ is the assigned anomaly of the climatic mean. The sample of $Q_{\max}^{warm}$ (or $Q_{\max}^{cold}$) is the sample of the annual maximum discharges observed in the years when annual air temperatures were higher (or lower) than the predetermined temperature threshold. Climatic mean of the annual maximum discharge for the "warm" years $Q_{\max}^{warm}$ was compared with the corresponding value in the "cold" years $Q_{\max}^{cold}$, and the aforementioned null hypothesis was tested by Mann-Whitney statistics (e.g. Sheskin, 2000). We used this non-parametric test because it gives reliable estimations for short samples of non-Gaussian variables, i.e. under the conditions when the classical parametric statistics, such as the Student's t-test, proved to be ineffective.

The same procedure was applied to construct series of $Q_{\min}^{warm}$ and $Q_{\min}^{cold}$. Then the Mann-Whitney statistics were applied as well to compare the climatic mean of the annual minimum discharge for the "warm" years $\overline{Q_{\min}^{warm}}$ with the corresponding value in the "cold" years $\overline{Q_{\min}^{cold}}$.

The used statistical tests have shown that the difference in the climatic means $\overline{Q_{\max}^{warm}}$ and $\overline{Q_{\max}^{cold}}$ is not statistically significant for almost all basins, in spite of the fact that the differences in the climatic mean of air temperatures in the "warm" and "cold" periods are rather large: for the Northern Dvina River basin the maximum difference was 3.9°C, the Pechora River basin −3.8°C, the Taz River basin −3.5°C, the Olenek River basin −2.9°C, the Indigirka River basin −2.2°C, and the Anadyr River basin −2.0°C. Significant changes of maximum runoff were found only for Yana River basin under the 4°C warming.

Minimum annual runoff turned out to be more sensitive to the annual temperature changes. Statistically significant changes were found in the Northern Dvina, Indigirka, and Yana river basins under conditions of warming of more than 1.7–2.8°C. At the same time, minimum annual runoff of the other considered rivers was not changed significantly, even under 3–4°C warming. The obtained results are summarized in Table 1.

Note, that the maximum or minimum flow could be, *a priori,* more sensitive to the seasonal temperature, but we analysed sensitivity of flow to the annual temperature because its existing regional projections are less uncertain than those of the seasonal temperature.

Table 1 Natural sensitivity of runoff to climate warming in the Arctic basin (NS, non-sensitive; S, sensitive).

River	Period of observations	Change of mean annual temperature				Change of mean annual temperature			
		+1°C	+2°C	+3°C	+4°C	+1°C	+2°C	+3°C	+4°C
		Maximum runoff				Minimum runoff			
Anadyr	1958–2008	NS	NS	NS	NS	NS	NS	NS	NS
Indigirka	1937–2005	NS	NS	NS	NS	NS	NS	S	S
N. Dvina	1882–2008	NS	NS	NS	NS	NS	NS	S	S
Olenek	1964–2007	NS	NS	NS	NS	NS	NS	NS	NS
Pechora	1932–2008	NS	NS	NS	NS	NS	NS	NS	NS
Taz	1962–2003	NS	NS	NS	NS	NS	NS	NS	NS
Yana	1972–2008	NS	NS	NS	S	NS	S	S	S

ASSESSING SENSITIVITY OF RUNOFF TO POSSIBLE CHANGES IN ANNUAL TEMPERATURE AND PRECIPITATION IN THE ARCTIC BASIN: A MODELLING APPROACH

The importance of the aforementioned issues requires advancing the current understanding of the hydrology of the Arctic region and developing, on this basis, adequate regional methods of hydrological simulation and prediction. The accumulated knowledge on the main specific features of the Arctic region hydrology has created a foundation for the development of the process-based hydrological models representing these features at different spatial scales, such as the models presented, for instance, by Kuchment *et al*. (2000), Zhang *et al*. (2000), Quinton *et al*. (2004), Gelfan (2005), Pomeroy *et al*. (2007), and Gusev *et al*. (2008). Parameters of such models have clear physical meanings and can be related to measurable characteristics of river basins, such as topography, soil, vegetation, etc. Combined with the physical background of the models, this feature provides new opportunities for obtaining reasonable results in the case of environmental changes, particularly to assess hydrological consequences of the projected climate change.

To analyse runoff sensitivity to climate change in the Arctic region, we have applied a physically-based distributed model ECOMAG (ECOlogical Model for Applied Geophysics) widely-used for simulation hydrological processes in large river basins of Russia and Scandinavia (Motovilov *et al*., 1999a,b; Gottschalk *et al*., 2001). The model describes the processes of snow accumulation and melt, soil freezing and thawing, water infiltration into unfrozen and frozen soil, evapotranspiration, the thermal and water regime of soil, overland, subsurface and channel flow. A river basin is schematized onto the landscape elements taking into account peculiarities of topography, soil and vegetation types, land use, etc.

A case study was carried out for the Lena River basin. The Lena River is one of the largest rivers in the Arctic that flow northward from mid latitudes to the Arctic Ocean (Fig. 1), and it contributes about 15% of total freshwater flow into the ocean (Shiklomanov *et al*., 2000). The catchment area is 2 460 000 km^2. Location of hydrometeorological gauges as well as topography and soil maps of the basin are shown in Fig. 3.

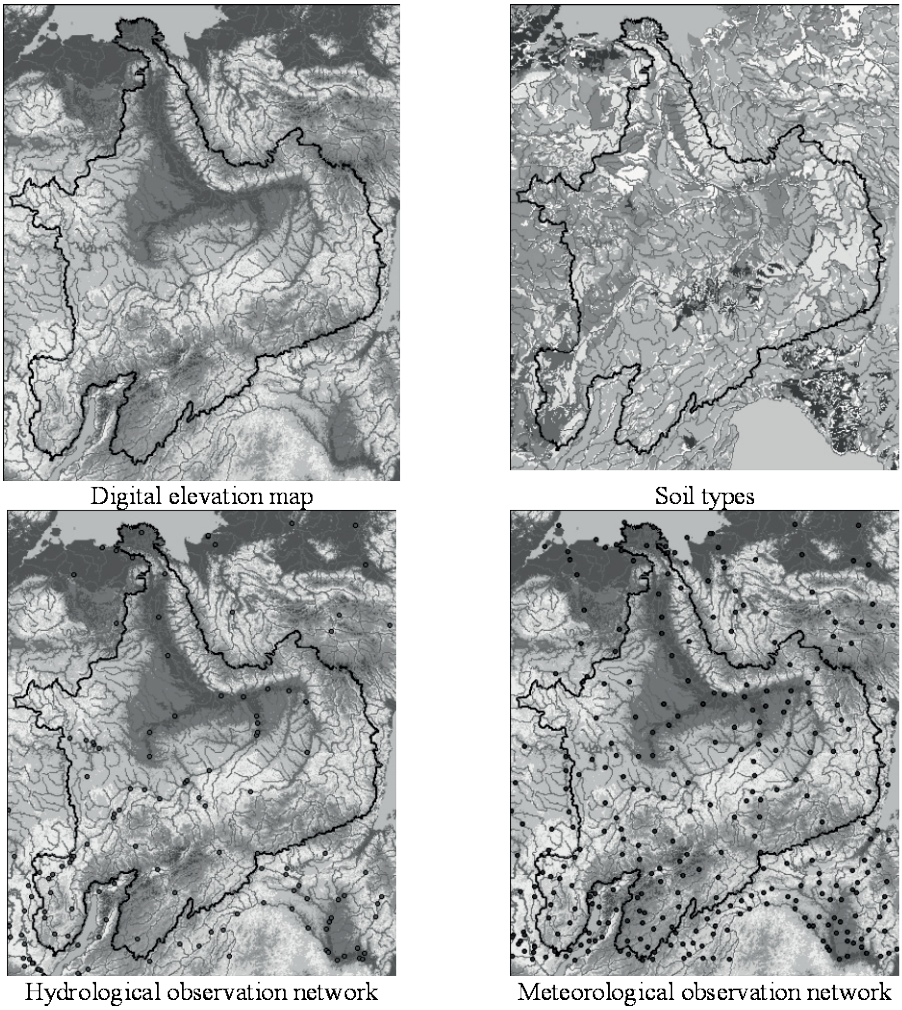

Fig. 3 Distributed information used for modelling runoff generation in the Lena River basin.

On the basis of the long-term (1935–1999) observations, remarkable changes of the Lena River hydrologic regime were identified by Yang *et al*. (2002) and Ye *et al*. (2003) as the consequence of the current climate warming and the related changes in permafrost conditions.

Calibration and validation of the model was carried out using time-series of daily discharge observations in the rivers of the Lena basin for the periods of 2000–2009 and 1987–1999, respectively. Comparison of the simulated and measured hydrographs at the basin outlet (Stolb station) for the validation period is shown in Fig. 4.

The Nash and Sutcliffe performance criteria calculated for different gauges at the Lena River and its tributaries are shown in Table 2.

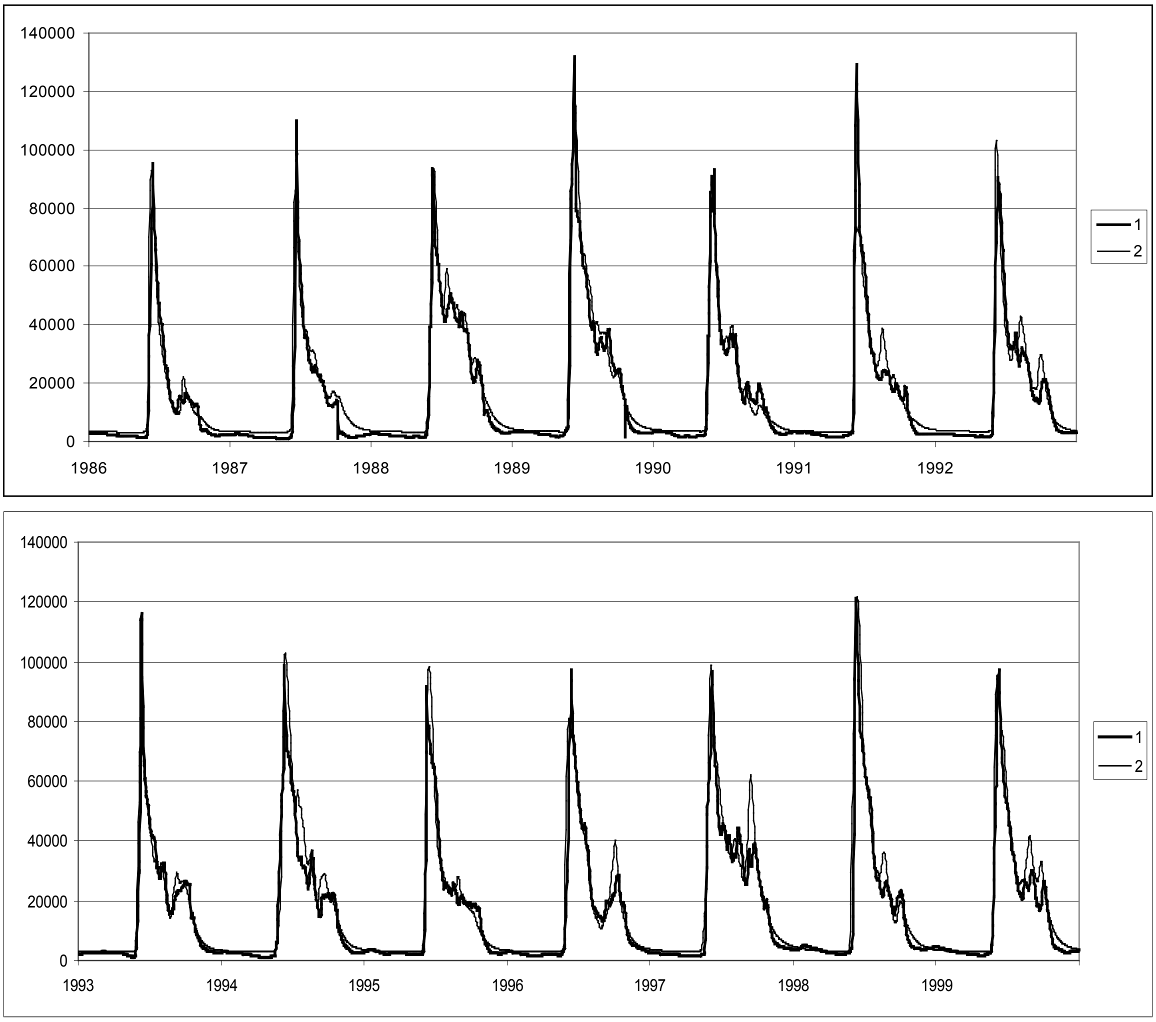

Fig. 4 Observed (1) and simulated (2) hydrographs at the Lena basin outlet (Stolb station) for the validation period (1987–1999).

Table 2 Nash and Sutcliffe efficiency of hydrograph (daily, monthly and quarterly) simulations.

River/Gauge	Catchment area, km^2	Daily	Monthly	Quarterly
Lena/Krestovsky	440 000	0.73	0.87	0.95
Lena/Solyanka	770 000	0.83	0.87	0.95
Lena/Tabaga	900 000	0.85	0.90	0.95
Lena/Stolb	2 460 000	0.86	0.90	0.93
Aldan/Okhotsky Perevoz	510 000	0.81	0.94	0.94
Aldan/Verkhoyansky Perevoz	696 000	0.79	0.93	0.90
Vilyui-Vilyuiskaya Hydropower Station	136 000	0.72	0.86	0.94
Olekma/Kudu-Kel’	120 000	0.71	0.90	0.89

Because of the absence of the accurate regional projections of climate, sensitivity of the Lena River runoff to climate change was assessed on the basis of the artificial scenario approach. The artificial time series of daily precipitation and air temperature were constructed from the corresponding observed series 2000–2009 by changing each daily value of the latter series by $\Delta P \in [-10\%,+20\%]$ and $\Delta T \in [-1.0^{\circ},+2.0^{\circ}]$, respectively. In other words, for the analysis of sensitivity, daily precipitation and temperature are assumed to be evenly changed for all the seasons. Note that this assumption can be rather crude for prediction of future runoff because it does not take into account that increase of warming and precipitation is, most likely, more intensive in the cold season.

Runoff hydrographs were simulated using different combinations of these artificial time series. The results of the numerical experiment are shown in Table 3.

Table 3 Sensitivity (%) of the simulated annual runoff of the Lena River to changes in mean annual air temperature and precipitation over the river basin.

ΔP, %	ΔT, °C			
	0	+1	+2	–1
0	0 (603 km^3)	–5	–11	5
+10	16	10	5	21
+20	32	26	20	38
–10	–16	–21	–26	–11

It was found that one degree warming leads to about five percent decrease of the simulated annual runoff as a result, primarily, of increasing simulated evapotranspiration associated with the deepening seasonal soil thawing in the Lena River basin. Ten percent wetting (without change in temperature) leads to a 16–17% increase of the simulated annual runoff.

CONCLUSION

Empirical and modelling approaches were used for assessing the Arctic river runoff sensitivity to changes in the annual climate characteristics. The empirical approach is based on the statistical analysis of differences between the observed runoff values in “warm” and “cold” years during the period of observations. For the majority of the considered basins, the differences were detected as statistically insignificant, in spite of large (up to 4°C) variations of the annual temperature observed in “warm” and “cold” years. The modelling approach is based on changing the observed time-series of daily temperatures and precipitation, simulating runoff hydrographs generated by the changed meteorological inputs and comparing these hydrographs with ones simulated under the unchanged (observed) inputs. Simulated runoff of the Lena River was found to be slightly sensitive to changes in climate characteristics: 10% decrease of runoff can be caused by 2° warming or 6–7% drying within the river basin.

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