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Climate noise effect on uncertainty of hydrological extremes: numerical experiments with hydrological and climate models

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Abstract. An approach has been proposed to analyze the simulated hydrological extreme uncertainty related to the internal variability of the atmosphere ("climate noise"), which is inherent to the climate system and considered as the lowest level of uncertainty achievable in climate impact studies. To assess the climate noise effect, numerical experiments were made with climate model ECHAM5 and hydrological model ECOMAG. The case study was carried out to Northern Dvina River basin (catchment area is 360 000 km^2), whose hydrological regime is characterised by extreme freshets during spring-summer snowmelt period. The climate noise was represented by ensemble ECHAM5 simulations (45 ensemble members) with identical historical boundary forcing and varying initial conditions. An ensemble of the ECHAM5-outputs for the period of 1979–2012 was used (after bias correction post-processing) as the hydrological model inputs, and the corresponding ensemble of 45 multi-year hydrographs was simulated. From this ensemble, we derived flood statistic uncertainty caused by the internal variability of the atmosphere.

1 Introduction

Analysis of meteorological data as well as climate model experiments show that the atmospheric circulation response to unprecedented (for the period of instrumental observations) global warming can lead to more persistent weather anomalies, that, in turn, may result in increase of flood hazard around the globe (e.g., Coumou and Rahmstorf, 2012). This is particularly the case for the northern extratropics influenced by strong Arctic warming and corresponding changes of temperature gradients and atmospheric circulation (e.g., Semenov, 2003; Cohen et al., 2014). However, the climate-driven changes in the magnitude/frequency of floods have not still evidently detected from the available streamflow records during the last decades or from streamflow simulation results (Kundzewicz et al., 2013; Merz et al., 2012; NRC, 2011; Olsen et al., 2010). Additional considerable uncertainty is inherent to projections of future flood changes. Evaluation of the impact of this inherent (structural) uncertainty is a key issue to realize the potential to obtain reliable assessments of climate-driven changes in hydrological systems (see, for instance, Koutsoyiannis et al., 2009). Natural variability of climate system (so-called "climatic noise") generated by stochastic fluctuations in atmosphere and ocean, is a major source of structural uncertainty in climate change projections and determines a lower limit of uncertainty that can be reached in climate system modeling (Braun et al., 2012). Important component of "climatic noise" is the internal atmospheric variability resulted from instability of atmospheric circulation to small perturbation of the atmospheric state. Our study is focused on transformation of the atmospheric variability by hydrological model and impact of this climatic noise component on uncertainty of simulated high-flow characteristics. To assess the climate noise effect, an approach presented by Gelfan et al. (2015) was applied. The approach is based on ensemble experiments with hydrologi-

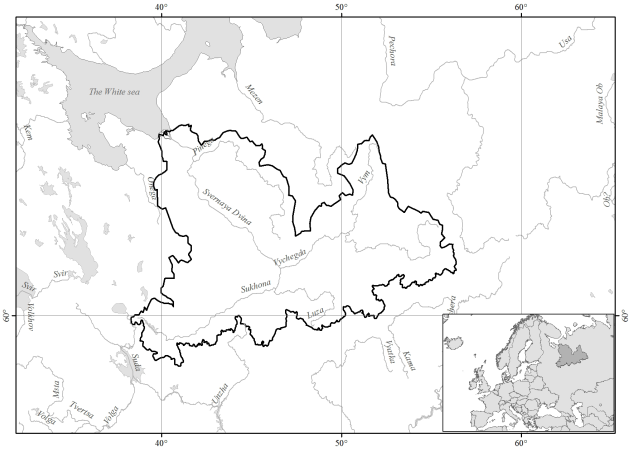

Figure 1. Location of the Northern Dvina River basin.

cal model ECOMAG driven by the atmospheric general circulation model (AGCM) ECHAM5 outputs simulated with identical historical boundary forcing and varying initial conditions for the current climate period (1979–2012). The case study was carried out for the Northen Dvina River basin with an area of 360 000 km^2 occupying vast flat forested territory in the northern part of East European plain and flowing northward to the White Sea basin (Fig. 1). The regional climate is characterized by long snow accumulation period resulting to spring freshet season when most part of the annual runoff flows (60 %, on the average).

2 Description of numerical experiments

The internal atmospheric variability was represented by large ensemble simulations (45 members) with the ECHAM5 AGCM. The model version used here has a horizontal resolution of T63 (1.8° × 1.8° latitude × longitude) and 31 vertical levels (Roeckner et al., 2003). This model has been extensively used for climatic research and, in particular, was found to reproduce climate change in the northern high latitudes very well when forced with historical SST and SIC data (Semenov and Latif, 2012). Forty five ensemble simulations used identical prescribed lower boundary conditions (atmosphere-ocean interface) taken from HadISST1.1 dataset that consists of global empirical analysis of sea surface temperature (SST) and sea ice concentrations (SIC) for 1979–2012 and constant external forcing parameters (Rayner et al., 2003). The only differences between the simulations were initial conditions of the atmosphere (model atmospheric state at the 1 January of 1979) that were prescribed as instant atmospheric states at different 12 h intervals in December 1978.

The ensemble of the ECHAM5-outputs for the period of 34 years (from 1 January 1979 to 31 December 2012) was used as the distributed input into ECOMAG hydrological model. Physically-based semi-distributed model ECOMAG (ECOlogical Model for Applied Geophysics) had been widely utilized for hydrological applications in many river basins of very different size and physiographic conditions (e.g., Motovilov et al., 1999; Motovilov and Gelfan, 2013; Gelfan et al., 2014). Particularly, Krylenko et al. (2014) used ECOMAG for simulating runoff hydrographs on the basis of multi-year hydrometeorological observations in the Northern Dvina River basins and demonstrated good performance of simulation (overall Nash-and-Sutcliffe efficiency criterion for daily discharge simulations is 0.90; Fig. 2).

A post-processing procedure was applied to correct biases in ECHAM5-outputs before using them as inputs into the hydrological model. In accordance with (Gelfan et al., 2015), the correction factors were computed based on the difference between the ensemble-mean climate variables modeled for the reference period and the corresponding observed gauge-based variables averaged over the basin area.

Forty-five-member ensemble of 34-year time-series of daily discharge (q_{ijk}; $i = 1, \ldots, 45$; $j = 1979, \ldots 2012$; $k = 1, \ldots, 365$) was simulated by the ECOMAG. Three ensembles of independent high-flow severity indicators were obtained from these time-series: (1) ensemble of annual cumulative duration D_{ij} (QT) of the hydrograph fragments above a pre-assigned daily streamflow threshold $\mathrm{QT} \equiv \mathrm{const}$, i.e. $D_{ij}\ (\mathrm{QT}) = \sum_{k=1}^{365} X_{ijk}$, where $X_{ijk} = \begin{cases} 1, q_{ijk} > \mathrm{QT} \\ 0, q_{ijk} \le \mathrm{QT} \end{cases}$; (2) ensemble of annual average discharge $Q_{ij}(\mathrm{QT})$ of the hydrograph fragments of $q_{ijk} > \mathrm{QT}$, i.e. $Q_{ij}(\mathrm{QT}) = \frac{1}{D_{ij}(\mathrm{QT})} \sum_{k=1}^{365} Y_{ijk}$, where $Y_{ijk} = \begin{cases} q_{ijk}, q_{ijk} > \mathrm{QT} \\ 0, q_{ijk} \le \mathrm{QT} \end{cases}$, and (3) ensemble of annual maximum daily discharge QMAX_{ij}.

3 Results and discussion

To illustrate differences between individual ensemble members arising from the internal atmospheric dynamics, Fig. 3 shows simulated ensembles of time series of the above high-flow severity indicators Q_{ij} (QT), D_{ij} (QT) and QMAX_{ij} ($i = 1, \ldots, 45$; $j = 1979, \ldots 2012$). (For this example, Q_{ij} (QT) and D_{ij} (QT) were calculated under the daily discharge threshold of $\mathrm{QT} = 6200\ \mathrm{m^3\,s^{-1}}$; this value was taken from flow duration curve under the exceedance level of 10 %). The values of the same indicators obtained from the observed streamflow data (Q_j^{obs} (QT), D_j^{obs} (QT) and $\mathrm{QMAX}_j^{\mathrm{obs}}$; $j = 1979, \ldots 2012$) and the corresponding values averaged over the simulated ensembles ($\overline{Q}_j\ (\mathrm{QT}) = \sum_{i=1}^{45} Q_{ij}/45$; $\overline{D}_j\ (\mathrm{QT}) = \sum_{i=1}^{45} D_{ij}/45$ and $\overline{\mathrm{QMAX}}_j = \sum_{i=1}^{45} \mathrm{QMAX}_{ij}/45$) are also shown in Fig. 3.

One can see from Fig. 3 that individual realizations within the ensemble significantly differ from each other and are only slightly correlated with the time-series of the corresponding indicators obtained from the observation data. Cor-

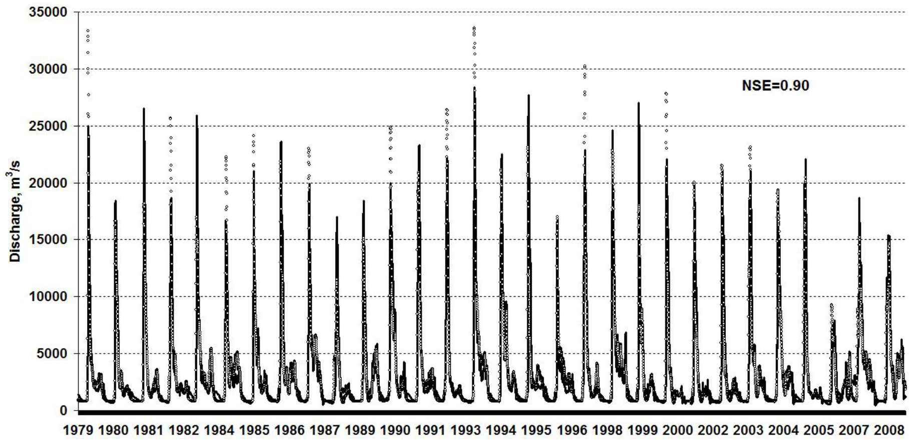

Figure 2. Observed (solid line) and simulated (points) hydrographs of the Northern Dvina river.

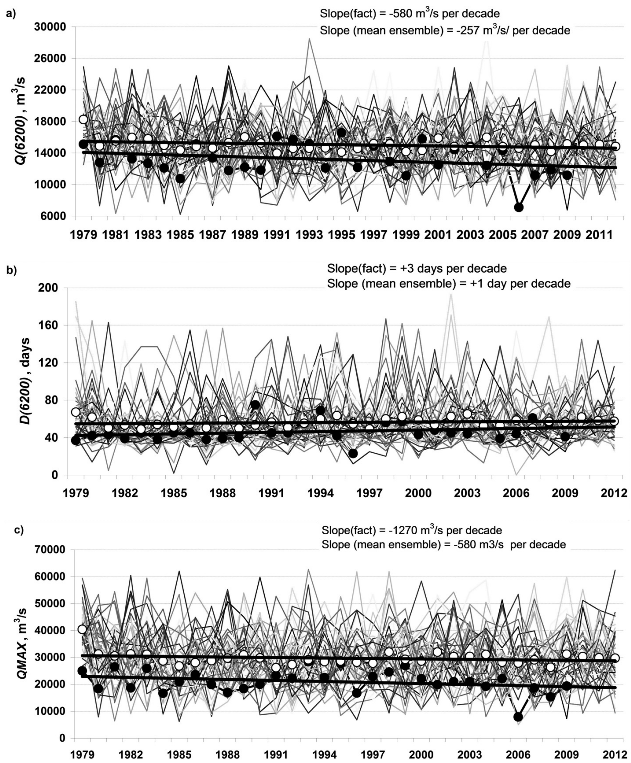

Figure 3. Observed (line with black markers) and simulated series of above-threshold average annual discharge **(a)**, above-threshold hydrograph duration **(b)** and annual maximum daily discharge **(c)**. Lines with white markers show the ensemble-averaged variables, thick lines show trends of the observed and the ensemble-averaged time series.

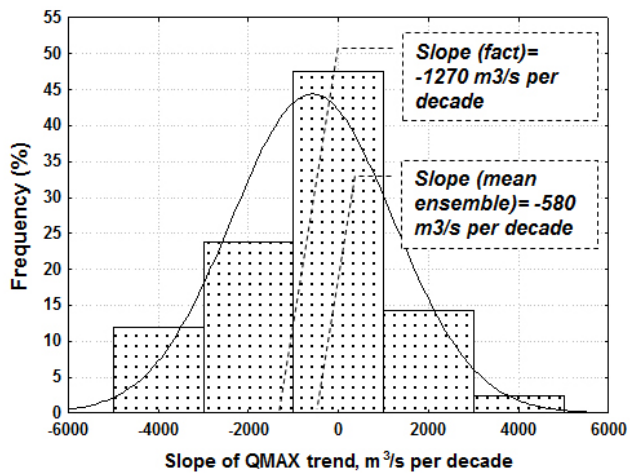

Figure 4. Histogram of the linear trend slope derived from the ensemble of simulated annual maximum discharge time series (line shows fitted normal distribution curve).

relation coefficients of Q_{ij} with Q_j^{obs}, D_{ij} with D_j^{obs} and QMAX_{ij} with $\mathrm{QMAX}_j^{\mathrm{obs}}$ vary over wide intervals, namely, [−0.28; +0.37], [−0.30; +0.40] and [−0.38; +0.44] with the mean values of 0.01, 0.01 and 0.05, respectively. Thus, because of the stochastic atmospheric variability effect, an individual realization, which is produced by a hydrological model operating on outputs from AGCM, does not contain any reasonable information on year-to-year changes in the specific hydrological variables under consideration.

At the same time, information on long-period hydrological changes can be extracted by averaging over the ensemble of individual realizations. Averaging allows us filtering a stochastic component caused by atmospheric variability and assessing the impact of "signal" caused by the external to the atmosphere factors (SST and SIC in our experiments). In Fig. 3, linear trends of the ensemble-averaged variables $\overline{Q}_j$, $\overline{D}_j$ and $\overline{\mathrm{QMAX}}_j$ with the corresponding trends of Q_j^{obs}, D_j^{obs} and $\mathrm{QMAX}_j^{\mathrm{obs}}$ are compared. One can see that tendencies in the observed variable long-term changes are reproduced by the ensemble averaged simulated time-series. The most visible negative trend was detected and generally reproduced

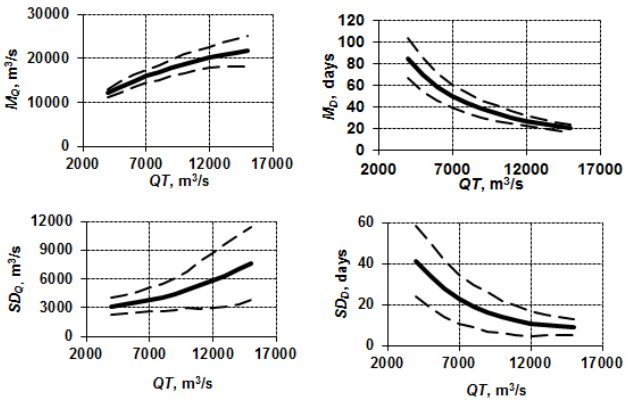

Figure 5. Estimates of high-flow statistics (solid lines) and bounds of their 99 %-confidence interval (dashed lines) in dependence on the threshold daily discharge value QT.

in the annual maximum discharge series. Insignificant negative trend was obtained also in the annual above-threshold average discharge series. We found that trend slopes of the individual realizations are close to symmetrically distributed around the ensemble mean that indicates that a considerable portion of the observed trend can be externally driven. As an example of the above statement, Fig. 4 demonstrates histogram of the trend slopes of annual maximum discharge obtained for each ith time-series QMAX_{ij} ($j = 1979, \ldots 2012$) shown in Fig. 3.

As shown above, the hydrological model driven by the ensemble of climate simulations is confined to making only projections of statistical characteristics of runoff series. Intra-ensemble dispersion of the individual realizations allows us assessing sample variance of these characteristics as measure of their uncertainty. The following statistics were estimated by the method of moments from the obtained ensembles: the overall mean values of the above-threshold hydrograph duration, M_D and the above-threshold average discharge, M_Q, as well as the overall standard deviations of these high-flow indicators (SD_D and SD_Q, respectively). Then, 99 % confidence intervals of these estimates were calculated taking into account sample variance of the corresponding statistics as measure of their uncertainty. Whilst calculating the confidence intervals, it was assumed that the estimates followed the Gaussian probability distribution

Figure 5 demonstrates M_Q, M_D SD_Q and SD_D values derived from the ensemble experiment described above in dependence on the assigned threshold daily discharge value QT. 99 %-confidence intervals of the derived statistics are also shown in Fig. 5.

As one can see, the internal atmospheric variability leads to significant uncertainty of the high-flow statistics. For SD-estimates, widths of the confidence interval can reach dozens percent of the corresponding statistic estimate, and, unsurprisingly, they are relatively larger than that for M-estimates. Uncertainty of the above-threshold average discharge statistics became wider with increase of QT, while the uncertainty of the above-threshold hydrograph duration behaves in an opposite way: the higher threshold, the less intra-ensemble variance of the annual duration of hydrograph fragments above this threshold. This can be explained by the fact, that the duration changes are inversely proportional to changes in the average discharge.

4 Conclusions

Due to inherent stochastic component of climate variability, hydrological model operating on outputs from an AGCM can not provide predictions (neither in the past nor, a fortiori, in the future) of specific streamflow hydrograph series. The model is confined, as well as a climate model, to making only projections of statistical characteristics of runoff time-series (Refsgaard et al., 2014). Taking into account this notion, we analyzed uncertainty of high-flow statistics (trend, mean and standard deviation) caused by the internal atmospheric variability component of the climate noise. The uncertainty was derived and assessed from the ensemble experiments with climate ECHAM5 AGCM and hydrological model ECOMAG. On the basis of these experiments, we found:

1. Individual realizations of the simulated high-flow severity indicator series for the period of 1979–2012 considerably differ from each other and are insignificantly correlated with the corresponding observed time series. In other words, simulated individual realization *per se* doesn't provide any useful information on the specific hydrological time series.

2. The averaging over large ensemble members effectively filters stochastic term related to the climate noise and results in an estimate of the externally forced signal, i.e. global sea surface temperature and sea ice concentration changes, in our experiments. We found that hydrological simulations, being averaged, satisfactory reproduce the observed general tendency in the high-flow statistics of the Northern Dvina River. This indicates that a portion of the observed trend in annual maximum discharge during 1979–2012 can be externally driven

3. The internal atmospheric variability component of the climate noise leads to significant high-flow statistic uncertainty that can reach dozens percent. Importantly, this is the lowest level of uncertainty achievable in climate impact studies, and this level will rise if "forcing" and "climate model" uncertainties (e.g., Hawkins and Sutton, 2009) are taken into consideration in addition to climate noise

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