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Simulating river flow to the Baltic Sea from climate simulations over the past millennium

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The aim of this study was to reconstruct river flow to the Baltic Sea using data from different periods during the past thousand years. A hydrological model coupled to simulations from climate models was used to estimate river flow. A “millennium” simulation of past climate from the ECHO-G coupled atmosphere–ocean global climate model provided climatological inputs. Results from this global model were downscaled with the RCA3 regional climate model over northern Europe. Temperature and precipitation from the downscaled simulation results were then used in the HBV hydrological model to simulate river flows to the Baltic Sea for the periods 1000–1199 and 1551–1929. These were compared with observations for the period 1921–2002. A general conclusion from this work is that although climate has varied during the past millennium, variability in annual river flow to the Baltic Sea does not appear more pronounced in recent years than during the previous millennium, or vice versa.

Introduction

The inflow from rivers to the Baltic Sea is an important variable for both physical and ecological processes of this semi-enclosed brackish sea. Examining how this has varied in the past provides a baseline for comparison with more recent periods and projected future conditions. Observations of river flow to the Baltic Sea are available for most of the previous century (Mikulski 1982, Bergström and Carlsson 1994). However, looking further back in time requires alternative methods of estimation.

The aim of this study was to reconstruct river flow to the Baltic Sea from different periods during the past thousand years. A hydrological model coupled to simulations from climate models was used to reproduce estimates of river flow. Climate models are most often used to produce scenarios for future climate, but they can also be used to reproduce climate that has occurred in the past. The focus of such exercises is generally to estimate the past range of variability of different climate variables, which is important for putting recent climate extremes into proper historical perspective.

This study uses a “millennium” simulation of past climate produced by a coupled atmosphere–ocean global climate model (GCM). Results from that model were downscaled using a regional climate model (RCM) over northern Europe. Temperature and precipitation from the downscaled simulation results were then used to drive a hydrological model that simulates river flows to the Baltic Sea.

Modelling methods

Millennium climate simulations

Global climate model simulations

The global climate model ECHO-G (Legutke and Voss 1999, Min *et al*. 2005) consists of the atmospheric model ECHAM4 (Roeckner *et al*. 1999) coupled to the ocean model HOPE-G (Wolff *et al*. 1997). ECHO-G has a horizontal grid resolution of about 3.75° for the atmosphere and 2.8° for the ocean with increasing resolution reaching 0.5° at the equator. The number of vertical levels is 19 for the atmosphere and 20 for the ocean. The simulation used here covering the past millennium is described in detail in González-Rouco *et al*. (2003) and von Storch *et al*. (2004). It is based on reconstructed forcing from three major external variables estimated from ice core data: (i) annual global concentrations of CO_2 and CH_4, (ii) volcanic radiative forcing, and (iii) solar radiative forcing. These estimates were combined in ECHO-G with historical sunspot observations (after around 1700).

Gouirand *et al*. (2006) discussed the uncertainties in the radiative forcings and concluded that the greenhouse gas forcing history is rather well known while the uncertainties acquainted with solar and volcanic forcings are larger. It should be noted that there are no anthropogenic aerosols in the model implying that an important forcing agent in the 20th century is absent. This suggests that the simulated warming trend in the 20th century is too strong, particularly over regions with strong emissions of sulfur such as Europe. Another issue with the simulation is that it starts from relatively warm initial conditions and was allowed only a 100 year spin-up time before the actual simulation period started. As discussed by González-Rouco *et al*. (2006) and Moberg *et al*. (2006) this implies that the conditions in the first part of the simulation are too warm. The lack of anthropogenic aerosols and warm initial conditions implies that the temperatures show a warm bias both in the early and late periods.

A comparison of model simulated data for Scandinavia to reconstructed data based on proxy information and also data from long instrumental records was done by Gouriand *et al*. (2006). Temperature series based on tree-rings for summer and ice break-up for winter were used together with instrumental data from Uppsala. They found reasonable agreement, meaning that both model and reconstructed records fluctuate around their long-term means during the first 500 years followed by cooling towards the coldest period around 1600–1650 and then gradual warming until the 20th century. The range of multi-decadal variability is about the same for the model, the reconstructions and the instrumental records although the fluctuations are not correlated in time. Also the warming trend from around 1600 to the early 20th century is of a similar size in the model and in the instrumental record. Based on these findings and additional analyses from Gouriand *et al*. (2006), Moberg *et al*. (2006) concluded that the 1000-year simulation with ECHO-G is sufficiently reliable for use in driving a regional climate model.

Regional climate model simulations

The ECHO-G output was downscaled over the Baltic Sea drainage basin by the RCA3 regional climate model (Kjellström *et al*. 2005). For this application, RCA3 was coupled with the FLAKE lake model (Mironov 2007) that was used to simulate sea surface temperatures (SST) and sea ice conditions for the Baltic Sea. Doing so makes considerable improvements to the results as compared to taking the coarser SST and sea ice directly from the global model. Simulations with RCA3 were carried out for three periods: 1000–1199, 1551–1749, and 1751–1929. The radiative forcing conditions applied were similar to the ones used in ECHO-G with the exception of the omission of changes in CH_4, since this greenhouse gas is not explicitly included in RCA3. The downscaling increased the horizontal resolution from 3.75° in the ECHO-G simulation to 1° on a regional domain chosen to focus on Scandinavia and surrounding parts of northern Europe. The number of vertical levels used was 24, with a time step of 30 minutes. Boundary data from ECHO-G, including SST and sea ice conditions for the north Atlantic, were input every 12 hours.

The RCA3 model using a 0.5° horizontal resolution was previously evaluated in a perfect boundary experiment with data from the ERA40 reanalysis (Uppala *et al*. 2005) for the period 1961–1999 (Kjellström *et al*. 2005). They showed that RCA3 can reasonably reproduce many features of the climate in Europe when provided with realistic boundary conditions. In general, seasonal mean temperature biases are rather small, less than ±1° in all of Europe with the exception of a stronger wintertime warm bias in northwestern Russia. Temperature biases in Scandinavia are positive during winter and negative during summer, reflecting a general overestimation of the cloud extent and cloud water content in the model. Precipitation generally agrees better with observations after downscaling, compared with the original ERA40 data, which shows the benefit of higher resolution.

Results from the RCA3 setup used here (i.e. with a coarser resolution, sea-ice and SSTs from FLAKE and ECHO-G boundary data) were evaluated by Moberg *et al*. (2006). They compared results from the simulation period 1901–1929 with gridded observations (CRU data; Mitchell *et al*. 2004). The comparison showed temperatures to be too high during winter and too low during summer. They also found excessive precipitation, particularly to the east of the Scandinavian Mountains as a result of the relatively coarse resolution. Overall, biases in the ECHO-G forced simulations were larger than those corresponding to ERA40-forced simulations. The RCA3 simulations were also compared with reconstructed and historical temperature series. The mean summer climate in northern Sweden was found to be 2–3° colder than what could be inferred from proxy data while the mean winter temperature in Estonia was close to observations. Despite biases, Moberg *et al*. (2006) concluded that the RCA3 simulation could be used for approximate estimation of the range of seasonal mean temperatures in Sweden during the last millennium. Comparing with daily temperature observations in Stockholm, however, they noted too many cold days and too few warm days in summer and autumn, while temperature distributions are better captured during winter and spring.

Hydrological simulations

The HBV hydrological model (e.g., Lindström *et al*. 1997) was used to reconstruct river flow to the Baltic Sea from the RCA3 downscaled millennium simulations. This is a conceptual, catchment-based, semi-distributed rainfall-runoff model that has been applied worldwide for drainage basins ranging in size from 1 km^2 to up to more than 100 000 km^2. It includes routines for soil moisture, evapotranspiration, snow accumulation and melt, runoff response, and storage routing.

Graham (1999) set up the HBV Model to simulate total river flow from the Baltic Sea drainage basin (HBV-Baltic). He calibrated HBV-Baltic for the period 1980–1986. Good performance was achieved, as measured by a Nash-Sutcliffe efficiency — R^2 (Nash and Sutcliffe 1970) — reaching 0.84 for total daily river flow to the Baltic Sea in an independent verification period (1986–1994). The version of HBV-Baltic used here simulates natural river flow to the Bothnian Bay and Bothnian Sea basins, whereby much of the regulation effects from reservoirs are removed. This is thought to better represent past conditions in these basins.

The monthly river runoff records used for calibration/verification are from all available measurement stations on rivers flowing into the Baltic Sea. This accounts for some 86% of the total drainage area. The remaining 14% of drainage area outside the network of flow measurements consists of coastal zones located between river mouths. Estimation of runoff from these areas came from specific runoff calculations using representative neighbouring stations (Bergström and Carlsson 1994).

The HBV-Baltic model has also been used to project effects of future climate (Graham 2004, Graham *et al*. 2007). In this study, the same setup was used; Fig. 1 shows the subbasins considered. However, results for the entire Baltic Sea drain-

Fig. 1. Principal Baltic Sea drainage basins used in HBV-Baltic. The Baltic Proper is shown in lighter grey as it was not included in this study.

age basin could not be obtained as the RCA3 domain used here did not completely cover the southernmost subbasins. For this reason, river flow to the Baltic Proper could not be included and simulation results focus on the Bothnian Bay, the Bothnian Sea, the Gulf of Finland and the Gulf of Riga.

Precipitation and temperature data are averaged over large subbasin areas and input to the model on a daily basis. For the original calibration/verification stage, these inputs came from a 1° gridded dataset of synoptic station data. As the spatial resolution of the observed dataset corresponds quite closely to the spatial resolution of the RCA3 millennium simulations, little additional error is thought to be introduced by the averaging process. Within each of the subbasins, both temperature and precipitation are further distributed with the application of lapse rates for elevation differences. This is important with respect to both snow and evapotranspiration processes, both of which rely on temperature-based methods of calculation.

Adjustment of precipitation and temperature

Before being used in the hydrological model, precipitation and temperature from the RCA3 simulation were adjusted to fit the daily observations used in Graham (1999). As these observa-

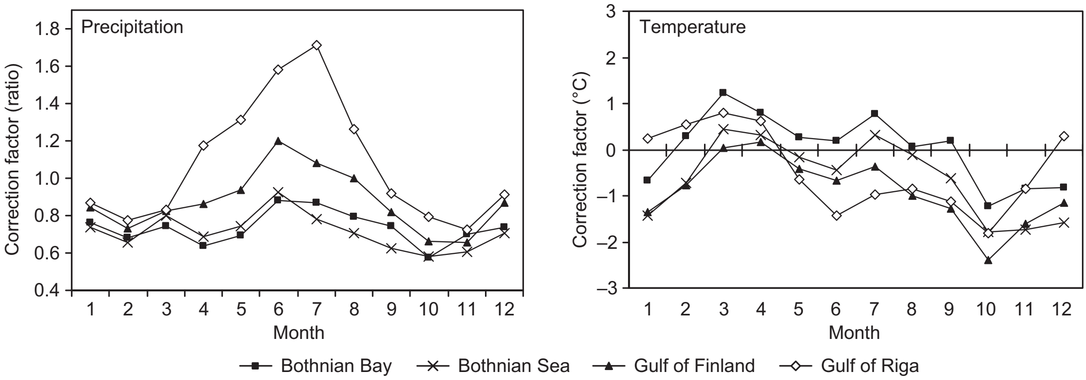

Fig. 2. Precipitation and temperature correction factors for each of the four main Baltic Sea drainage basins used here.

tions start only in 1980 (currently updated to 2007) and the RCA3 simulations end in 1929, the CRU climate database (Mitchell *et al*. 2004) was used in an intermediate step. CRU data were available for the period 1901–2002.

Precipitation and temperature adjustment was done with subbasin-specific monthly correction factors, multiplicative for precipitation and additive for temperature. To calculate monthly factors, the gridded RCA3 simulation outputs for the period 1901–1929 and CRU data for the periods 1901–1929 and 1980–2002 were interpolated into daily subbasin averages to conform to the observations used in Graham (1999). As a first step in the adjustment, monthly subbasin averages for 1980–2002 observations and CRU data were compared, yielding correction factors that make the CRU data conform to these observations. In the second step, corrected CRU data in the period 1901–1929 were compared with RCA3 simulation outputs for the same period. This gave the total correction required to make the RCA3 data conform to the original observation data used to calibrate HBV-Baltic.

Regarding precipitation correction factors, most fall below 1, with June and July being exceptions (Fig. 2). This implies that the RCA3 simulated precipitation is overestimated, which is in line with previous evaluation. For June and July a small adjustment to increase precipitation is needed. On average over the year, the correction factors lead to a reduction of precipitation by a factor 0.82. It can be noted that the percentage of dry days in the RCA3 simulation — approximately 15% — agrees well with observations at these large basin scales.

Regarding temperature correction factors, most adjustments are negative, except for March and April (Fig. 2). This implies that RCA3 simulated temperatures are overestimated. Generally, however, the correction required is rather small, mostly within ±1 °C. On average over the year, temperature is reduced by 0.6 °C.

Results

The above corrections were applied to all three simulation periods (1000–1199, 1551–1749, and 1751–1929) and HBV-Baltic simulations were performed (Figs. 3–6).

Common to all of the results is that observed mean temperatures (1980–2002) are all higher than those simulated for the past millennium. Mean precipitation observations for the Bothnian Bay and the Bothnian Sea are also higher than values from the entire millennium simulation. For the Gulf of Finland, precipitation observations are higher than values seen in the millennium simulation period 1551–1929, but closer to the range of variability for the period 1000–1199. For the Gulf of Riga, observed precipitation falls within a similar range of variability as seen over the entire millennium simulation.

Regarding river flow, there are no remarkable trends apparent. Annual variability during the past century looks to fall within the range of the variability simulated over the past millennium

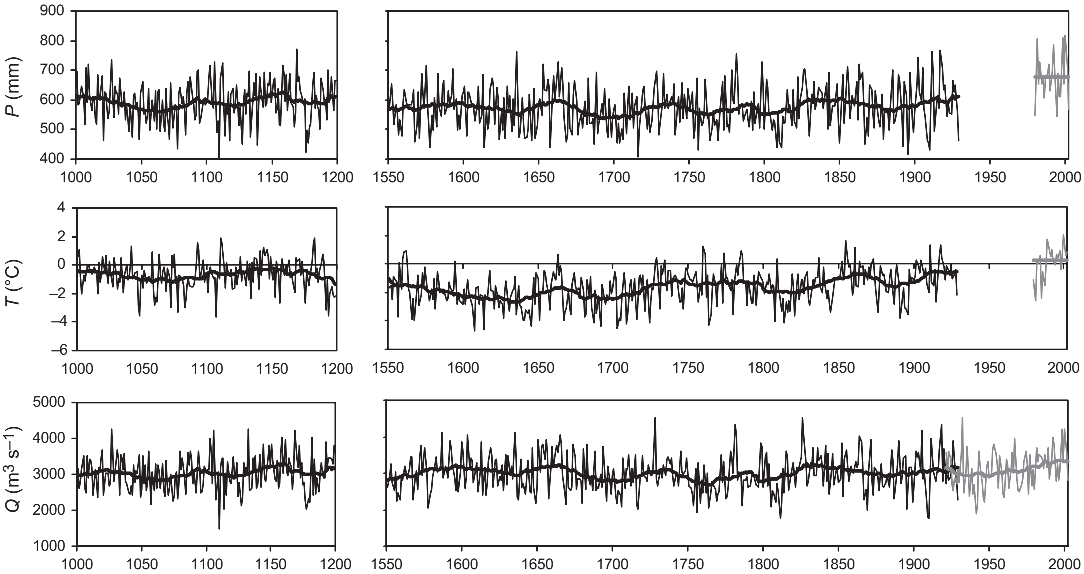

Fig. 3. Bothnian Bay annual precipitation (*P*), temperature (*T*) and river flow (*Q*). Precipitation and temperature are from RCA3 simulations, but have been adjusted according to the correction factors shown in Fig. 2. Simulated river flow comes from HBV-Baltic simulations. The thick trend lines show the 30-year moving average. Observations (1921–2002) are shown in grey.

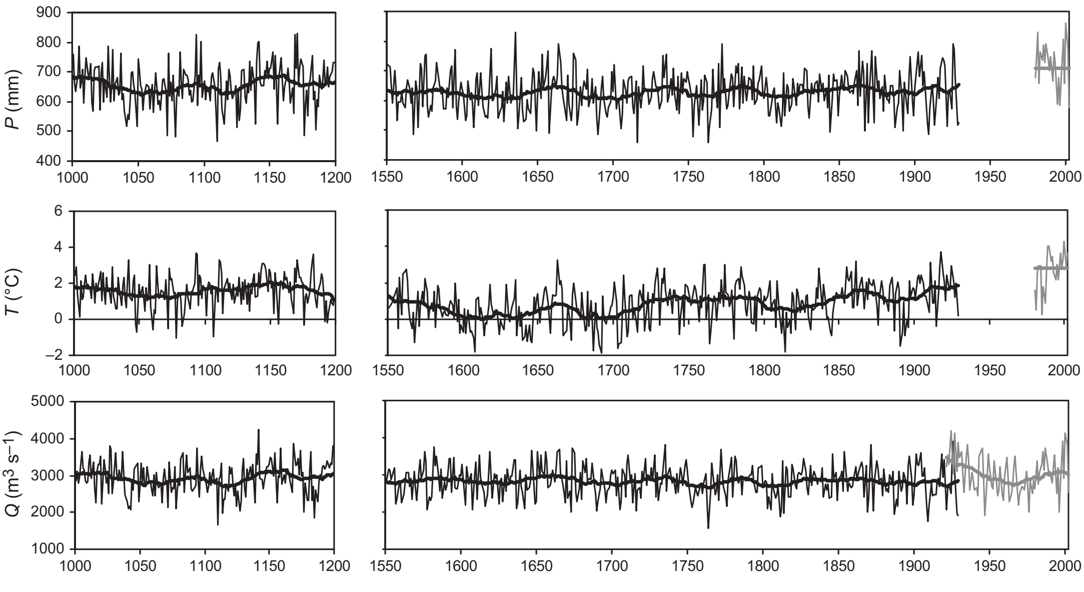

Fig. 4. Bothnian Sea annual precipitation (*P*), temperature (*T*) and river flow (*Q*). Precipitation and temperature are from RCA3 simulations, but have been adjusted according to the correction factors shown in Fig. 2. Simulated river flow comes from HBV-Baltic simulations. The thick trend lines show the 30-year moving average. Observations (1921–2002) are shown in grey.

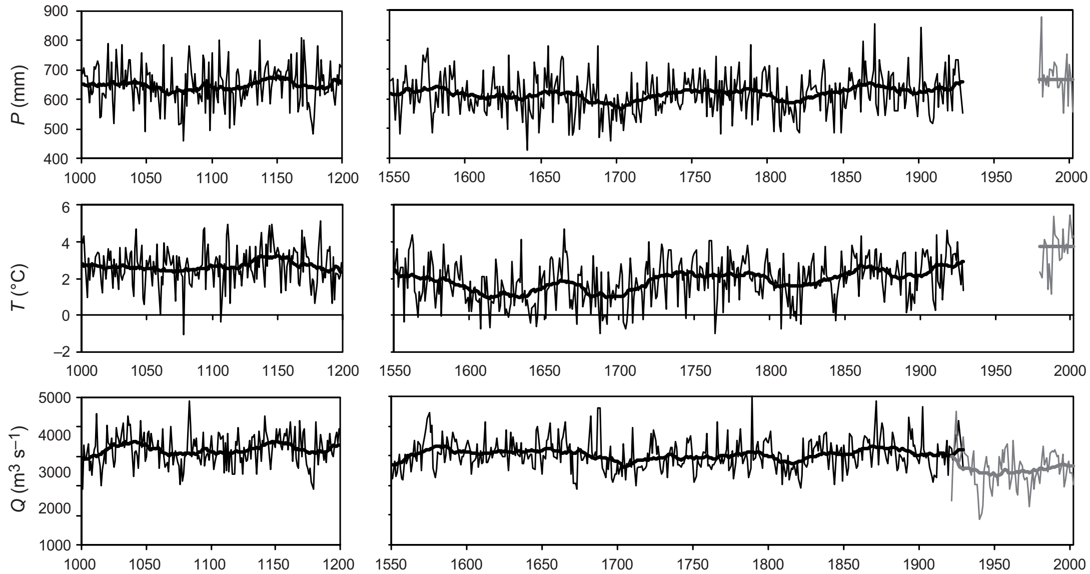

Fig. 5. Gulf of Finland annual precipitation (*P*), temperature (*T*) and river flow (*Q*). Precipitation and temperature are from RCA3 simulations, but have been adjusted according to the correction factors shown in Fig. 2 Simulated river flow comes from HBV-Baltic simulations. The thick trend lines show the 30-year moving average. Observations (1921–2002) are shown in grey.

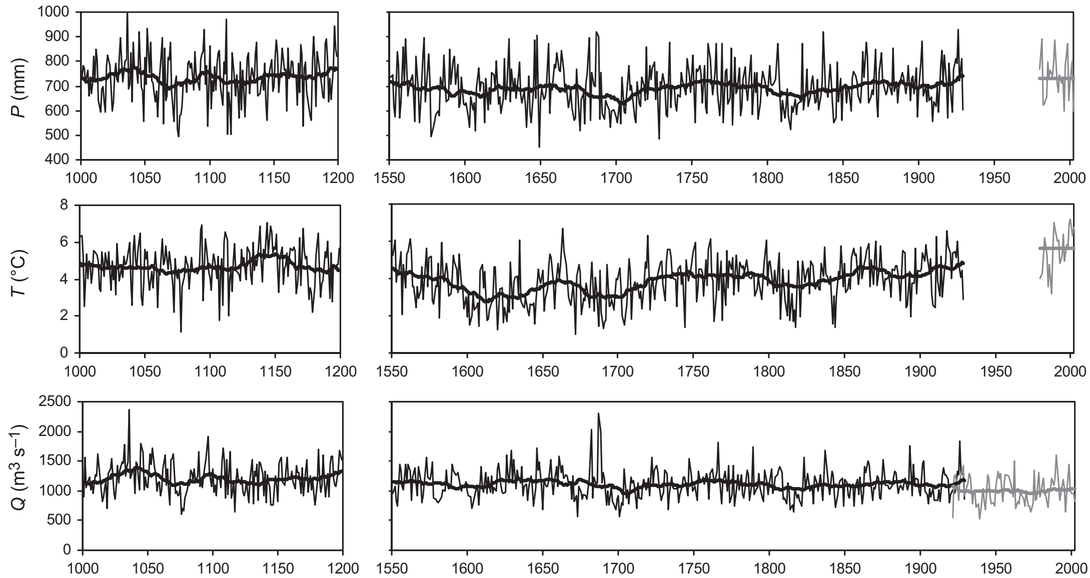

Fig. 6. Gulf of Riga annual precipitation (*P*), temperature (*T*) and river flow (*Q*). Precipitation and temperature are from RCA3 simulations, but have been adjusted according to the correction factors shown in Fig. 2. Simulated river flow comes from HBV-Baltic simulations. The thick trend lines show the 30-year moving average. Observations (1921–2002) are shown in grey.

(*see* Table 1). As indicated by the coefficient of variation, the annual variability during the simulated periods reaches values that are close to those for available observations. An exception is Gulf of Finland, where the coefficient of variation is lower in all of the simulated periods.

There are some other notable features in the river flow results. Whereas observed river flows for both the Bothnian Bay and the Gulf of Riga coincide well with simulated flow over the overlap period (1921–1929), this is not the case for the Bothnian Sea, which shows a discrepancy between observed and simulated values. Furthermore, results from the Gulf of Finland indicate a change in trend just at the overlap period.

Discussion

According to Moberg *et al*. (2006), examination of runoff generation coming directly from the RCA3 model indicates that river flow during the simulated previous millennium may have been higher than in the 20th century for southern parts of Sweden, but not in northern parts. Evaluation of the HBV-Baltic simulations concurs with this for northern Sweden (i.e. Bothnian Bay and Bothnian Sea). As the southernmost basins of Sweden were not included here, we cannot directly confirm the result for that area. However, looking at results for the Gulf of Riga that lies on similar latitudes to southern Sweden, higher river flow in the earlier periods is indicated, which concurs with Moberg *et al*. (2006). This is particularly true for the period 1000–1199.

Regarding river flow from the northern basins, one could speculate that increasing precipitation in the Bothnian Bay and the Bothnian Sea would lead to increasing river flow in recent years. This is not obvious here, although there is a slight increasing trend for the Bothnian Bay in the observations. Similar results were presented in a study of observations in Sweden over the 20th century by Lindström and Alexandersson (2004). They concluded that this may be partly explained by a compensating increase in evapotranspiration due to increasing temperatures. Both the Gulf of Finland and the Gulf of Riga showed lower river flow during the 20th century. The explanation here may also partly rely on increasing evapotranspiration with increasing temperature, as changes in precipitation in both of these basins is seen to be relatively low. This is particularly true for the Gulf of Finland, which

Table 1. Standard deviation (SD), mean and coefficient of variation (CV) of annual river flow summarised for selected intervals (80 to 100 years) over both the modelled and observed periods.

	Bothnian Bay			Bothnian Sea			Gulf of Finland			Gulf of Riga		
	SD ($m^3 s^{-1}$)	Mean ($m^3 s^{-1}$)	CV (%)	SD ($m^3 s^{-1}$)	Mean ($m^3 s^{-1}$)	CV (%)	SD ($m^3 s^{-1}$)	Mean ($m^3 s^{-1}$)	CV (%)	SD ($m^3 s^{-1}$)	Mean ($m^3 s^{-1}$)	CV (%)
Modelled												
1001–1100	427	2978	14.4	406	2924	13.9	553	4209	13.1	286	1227	23.3
1101–1199	527	3096	17.0	461	2934	15.7	519	4262	12.2	251	1194	21.0
Modelled												
1551–1650	469	3013	15.6	418	2822	14.8	480	4094	11.7	230	1125	20.5
1651–1750	499	3022	16.5	420	2891	14.5	547	3979	13.8	279	1095	25.5
1751–1850	524	2924	17.9	399	2771	14.4	512	3959	12.9	230	1105	20.9
1851–1929	542	3039	17.8	476	2818	16.9	541	4151	13.0	222	1116	19.9
Observed												
1921–2002	516	3107	16.6	514	3028	17.0	615	3543	17.4	230	1003	23.0
Maximum[1]	542	3107	17.9	514	3028	17.0	615	4262	17.4	286	1227	25.5
Minimum[1]	427	2924	14.4	399	2771	13.9	480	3543	11.7	222	1003	19.9
Range[1]	115	183	3.6	115	257	3.1	135	718	5.6	64	224	5.6

[1] Maximum and minimum are the highest and lowest of the values summarised in the column above; range is the difference between these two.

has many large lakes and thus a proportionately higher water surface to land ratio leading to a higher evaporation potential.

The correction factors applied to the RCA3 simulation outputs are not large, which increases our confidence in the simulated precipitation and temperature. Gulf of Riga is an exception as it shows a larger range of seasonal precipitation correction. Regarding the discrepancies in river flow between simulated and observed periods for the Bothnian Sea and to some extent the Gulf of Finland, these could be indicators that model biases for these areas are more pronounced than for the other sub-regions in the modelling domain. They could also reflect inhomogeneities in the observed datasets, which could mean that the correction factors may be less representative in some periods. Additional analysis is needed to explain this.

Due to the coarse model resolutions used, conclusions from this work should focus on the large scale, such as the scale of the main drainage basins to the Baltic Sea. Future work of this type would benefit from higher resolution in the regional climate model. Also, future applications should use a larger RCM domain that adequately covers the full Baltic Sea drainage basin so that analysis of the southernmost subbasins could be included. Limitations in computing resources prohibited this from being done in this study.

The models used can also affect the variability of simulated river flow. Although a detailed assessment of these effects is not presented here, it is thought from preliminary analysis that both the RCA3 and HBV-Baltic models contribute to some under representation of variability, of approximately similar magnitudes. However, as shown in Table 1, the annual variability over the large drainage basins is nevertheless reasonably represented in most of the results, as compared to observations. An exception is the Gulf of Finland, which shows lower variability for the simulated periods versus the observed period. This can partly be attributed to the dominance of large lakes in the drainage basin and how they are represented (Graham 2004). As these processes are simplified in the hydrological model, the full range of river flow response is somewhat limited and the interannual variability tends to be dampened.

Conclusions

According to the simulation results presented here, river flow to much of the Baltic Sea during the 20th century is not greatly different than in previous centuries, neither in variability or mean annual values. However, river flows to the eastern Baltic show lower annual river flow in the latest 50–75 years. This agrees with runoff generation results coming directly from the regional climate model. Simulated and observed values for river flow were in agreement in the overlapping decade for much of the modelled drainage basin, with the exception of the Bothnian Sea. Further explanation is needed for this discrepancy. The range of variability over the millennium simulation is deemed to be representative as documented climatological analyses judged the climate simulations to be credible, despite some identified biases. Correction factors for temperature and precipitation were needed to adjust climate model outputs to the climatology used to calibrate the hydrological model. Although this is thought to reduce systematic biases, it does introduce additional uncertainty in the results.

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