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Reconstruction of river runoff to the Baltic Sea, AD 1500–1995

Daniel Hansson,* Christin Eriksson, Anders Omstedt and Deliang Chen
Earth Sciences Centre, University of Gothenburg, SE-405 30 Göteborg, Sweden

ABSTRACT: In this paper we reconstructed river runoff to the Baltic Sea since 1500 using temperature and atmospheric circulation indices, showing the important atmospheric processes for river runoff in different regions. Runoff appears to be strongly linked to temperature, wind and rotational circulation components in the northern region and Gulf of Finland, but more associated with rotational and deformation circulation components in the south. No significant long-term change has been detected in total river runoff to the Baltic Sea for 500 years, although decadal and regional variability is large. Analysis of runoff sensitivity to temperature shows that the south region may become drier with rising air temperatures. This is in contrast to the north region and Gulf of Finland where warmer temperatures are associated with more river runoff. Over the past 500 years the total river runoff to the Baltic Sea has decreased by 3% (450 m^3/s) per degree Celsius increase. Copyright © 2010 Royal Meteorological Society

KEY WORDS Baltic Sea; river runoff; climate reconstruction; climate change; atmospheric circulation; statistical analysis; freshwater

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1. Introduction

Climate change is an ongoing process on all spatial scales around the globe, including in the Baltic Sea region in Northern Europe (Eriksson *et al.*, 2007). The air temperature increase in the Baltic Sea basin has been slightly greater than the global increase, and reduction in snow cover and sea ice extent has been detected on multi-decadal time scales (The BACC author team, 2008, hereafter BACC). To date, no significant changes in the water cycle have been identified, but such changes are expected to emerge more clearly in coming decades (Lindström and Alexandersson, 2004; BACC, 2008).

Due to the Baltic Sea's brackish nature, the salinity level is very important for its marine ecosystem. The salinity is highly dependent on freshwater inflow to the Baltic Sea, which comes either as river runoff due to precipitation over the drainage basin, or as net precipitation (precipitation minus evaporation) over the sea surface. Annual mean river runoff to the Baltic Sea is approximately 15 000 m^3/s and net precipitation over the sea surface approximately 1000 m^3/s (Omstedt *et al.*, 2004). The seasonal differences in the river runoff are great, ranging from maximal freshwater discharge during snowmelt in late spring and early summer (approximately 22 500 m^3/s) to minimum freshwater discharge in winter (approximately 13 000 m^3/s), when most precipitation comes as snow. The salinity of the Baltic Sea is determined by processes operating on a multi-decadal time scale (Omstedt and Hansson, 2006a, 2006b). Although there are uncertainties associated with climate scenarios regarding future precipitation in the region, these scenarios imply reduced (increased) river runoff in the southern (northern) parts of the Baltic Sea drainage area (Graham, 2004). Such a change may alter future salinity levels and potentially have a great impact on the ecosystem.

This paper reconstructs the freshwater discharge from the Baltic Sea drainage basin to the Baltic Sea since AD 1500 using statistical modelling. It also examines the characteristics of the variability in river runoff on decadal time scales and studies the temperature dependence of this variability. Applying a long-term perspective is important, so that any unusual or significant changes over the past century, when human impact has been great, can be more easily detected. Section 2 reviews the data and methods used, followed by the results and analysis in Section 3. Section 4 discusses the results and draws conclusions.

2. Method and data

We applied stepwise regression (Draper and Smith, 1966) to develop statistical models of river runoff for all four seasons of the year. The technique chooses predictors that contribute to the models at a significance level exceeding 0.08 on an F-test. This ensures that only predictors making a statistically significant contribution are implemented in the models. Input data were the reconstructed seasonal temperatures for the Baltic Sea (Luterbacher *et al.*, 2004; Hansson and Omstedt, 2008) and

* Correspondence to: Daniel Hansson, Earth Sciences Centre, University of Gothenburg, SE-405 30 Göteborg, Sweden.
E-mail: daniel.hansson@gvc.gu.se

the atmospheric geostrophic velocity field and rotational components described in Eriksson *et al.* (2007). These indices of the velocity field have been demonstrated to be useful indicators of atmospheric circulation (Chen, 2000) and are closely linked with precipitation in Sweden (Hellström *et al.*, 2001) and with sea level (Chen and Omstedt, 2005) and sea ice (Omstedt and Chen, 2001) over the Baltic Sea. The atmospheric indices used here are standardized predictors based on the updated $1° \times 1°$ gridded sea-level pressure reconstruction for Europe between AD 1500 and 1995 by Luterbacher *et al.* (2002). This way, information about the entire pressure field is obtained, which is assumed to describe atmospheric circulation patterns in the Baltic Sea drainage area better than a single circulation index such as the North Atlantic Oscillation (cf. Bouwer *et al.*, 2006). As candidate predictors the temperature and velocity field together with the temperatures and velocity fields for the two previous seasons were used. This two-season lag is applied as precipitation over the drainage area does not enter rivers and streams instantaneously. For example, most precipitation in winter comes as snow and does not enter the Baltic Sea via rivers until snowmelt occurs in spring or early summer. Therefore, runoff in summer may depend on the circulation patterns of previous seasons. The regression is calibrated against monthly sub-regional river runoff data from 1950 to 1995, provided by The BALTEX Hydrological Data Centre. Over this period the regulation of rivers discharging into the Baltic Sea increased. Estimates of monthly total river runoff for the 20th century have been published earlier (Mikulski, 1986; Cyberski and Wróblewski, 2000) and are used here in validating the statistical model over the 1901–1949 period. Standard error estimates for the regression statistics were calculated using bootstrapping with 10 000 replicates.

The climate in the Baltic Sea drainage basin is influenced by dry continental air masses in the north and east and humid maritime conditions in the south and west (BACC, 2008). The stepwise regression model was therefore applied to three sub-regions of the Baltic Sea: a northern region representing the Bothnian Bay and the Bothnian Sea, an eastern region representing the Gulf of Finland, and a southern region consisting of the remainder of the Baltic Sea. This division allows for circulation patterns to differ between the three sub-regions. In the northern region, colder and drier air masses prevail and are often governed by the strengthening or weakening of the Russian high, while the southern region usually has milder temperatures and more humid air due to the influence of North Atlantic cyclonic activity. Gulf of Finland is essentially dominated by the same atmospheric circulation patterns as the northern region, but as it is also modulated by two large lakes, Lake Ladoga and Lake Onega, the river runoff in this region shows less interannual variability.

3. Results

The seasonal specific equations resulting from the stepwise regression procedure are presented in Table I. There is no general atmospheric circulation feature common to all seasons and regions. The somewhat different characteristics of the three sub-regions can be seen in the model

Table I. The equations resulting from the stepwise regression routine and corresponding correlation coefficient (r).

							r
The southern region of the Baltic Sea							
$Q_f^{\mathrm{Winter}} =$	6135	$-857D_2^{\mathrm{DJF}}$	$+728R^{\mathrm{JJA}}$	$-710U^{\mathrm{SON}}$	$-609D_1^{\mathrm{DJF}}$	$+494V^{\mathrm{DJF}}$	
		$-432D_1^{\mathrm{SON}}$	$+374R^{\mathrm{SON}}$				0.85
$Q_f^{\mathrm{Spring}} =$	8534	$+1285R^{\mathrm{MAM}}$	$-1036T^{\mathrm{DJF}}$	$+832R^{\mathrm{DJF}}$	$+449E^{\mathrm{DJF}}$	$+301V^{\mathrm{MAM}}$	0.91
$Q_f^{\mathrm{Summer}} =$	3770	$-367T^{\mathrm{MAM}}$	$+367R^{\mathrm{MAM}}$	$+297D_1^{\mathrm{MAM}}$	$-259T^{\mathrm{JJA}}$		0.62
$Q_f^{\mathrm{Autumn}} =$	4612	$+984R^{\mathrm{JJA}}$	$+502R^{\mathrm{SON}}$				0.71
The northern region of the Baltic Sea							
$Q_f^{\mathrm{Winter}} =$	4120	$+526U^{\mathrm{DJF}}$	$-379T^{\mathrm{JJA}}$	$-297E^{\mathrm{JJA}}$	$-260D_1^{\mathrm{SON}}$		0.68
$Q_f^{\mathrm{Spring}} =$	7344	$+793T^{\mathrm{MAM}}$	$+446R^{\mathrm{DJF}}$	$-245T^{\mathrm{SON}}$			0.72
$Q_f^{\mathrm{Summer}} =$	7123	$+604R^{\mathrm{JJA}}$	$-592V^{\mathrm{MAM}}$	$+459E^{\mathrm{MAM}}$			0.57
$Q_f^{\mathrm{Autumn}} =$	5472	$+595R^{\mathrm{JJA}}$	$-510D_1^{\mathrm{SON}}$	$+438V^{\mathrm{JJA}}$			0.60
Gulf of Finland							
$Q_f^{\mathrm{Winter}} =$	2648	$+184U^{\mathrm{DJF}}$	$-175T^{\mathrm{JJA}}$	$-158D_1^{\mathrm{JJA}}$	$+144T^{\mathrm{SON}}$		0.64
$Q_f^{\mathrm{Spring}} =$	4212	$+240U^{\mathrm{MAM}}$					0.35
$Q_f^{\mathrm{Summer}} =$	3903	$+238R^{\mathrm{DJF}}$					0.40
$Q_f^{\mathrm{Autumn}} =$	3735	$-303T^{\mathrm{JJA}}$	$+213T^{\mathrm{SON}}$				0.52

The predictors are near-surface air temperature (T), zonal wind (U), meridional wind (V), vorticity (R), divergence (E), shear (D_1) and normal deformation (D_2). All indices are season specific and annotated accordingly, where DJF is winter, MAM is spring, JJA is summer and SON is autumn.

equations. Over all seasons, the most important atmospheric circulation indices for the southern region are the rotational and deformation components. Physically, this means that the strength and torque of the cyclonic or anticyclonic pressure systems are important to the freshwater discharge. The rotational, zonal and meridional wind components and temperature are the most important factors for the northern region, while temperature and wind primarily influence the runoff in the Gulf of Finland. This is expected, as zonal and meridional wind produce different rainfall responses. Westerly winds are often associated with humid air from the North Atlantic, while northerly winds tend to advect dry air into the region. That the strength of the rotational components (where positive and negative values denote cyclonic and anticyclonic systems, respectively) are major influences on freshwater discharge in the northern region, but not in the Gulf of Finland, is also expected, as powerful cyclonic systems bring more precipitation than do weaker ones. For the Gulf of Finland, lag and dampening from the large lakes somewhat diminish this effect. Note that the autumn season in all sub-basins is dependent on vorticity as high sea surface temperatures create unstable conditions and higher atmospheric moisture content (Linderson *et al.*, 2004).

The seasonal and basin specific correlation coefficients displayed in Table I are calculated for the 1950–1995 calibration period, and they indicate that the established relationships for the southern and northern region are fairly reliable. Although the winter, spring and autumn conditions are successfully described, summer is not well modelled for all regions. This indicates that other factors such as local and oreographic effects, which are not well described by the atmospheric indices, may be important. The Gulf of Finland model displays less skill than do the models of the other two regions; this is because it is dampened by lakes Onega and Ladoga, resulting in a more complex system with other lags and a two-lake overflow dynamics.

The reconstructed annual total river runoff to the Baltic Sea for the 1901–1995 period is shown in Figure 1(a). The correlation coefficient for the calibration period is 0.75 ± 0.07 and for the validation period is 0.56 ± 0.09. By testing the skill of the reconstruction both the reduction of error (RE) and coefficient of efficiency (CE) was calculated to be 0.28 ± 0.13. Values greater than zero implies reconstructive skill, and that the reconstruction is better than climatology (Cook *et al.*, 1994). Meanwhile, the root mean square error (RMSE) is estimated to be 1332 ± 120 m^3/s, indicating that extreme annual values are not well captured. This is a general problem with linear regression techniques, but should not have any long-term effect on the Baltic Sea salinity balance as it operates on the order of several decades (e.g. Omstedt and Hansson, 2006a, 2006b). All in all the reconstruction do have reconstructive skill, albeit associated with uncertainties. The full reconstruction can be seen in Figure 1(b). Mean annual river runoff over the 1500–1995 period is $15\,420 \pm 900$ m^3/s, consistent with previous observational studies of the 20th century (e.g. Cyberski and

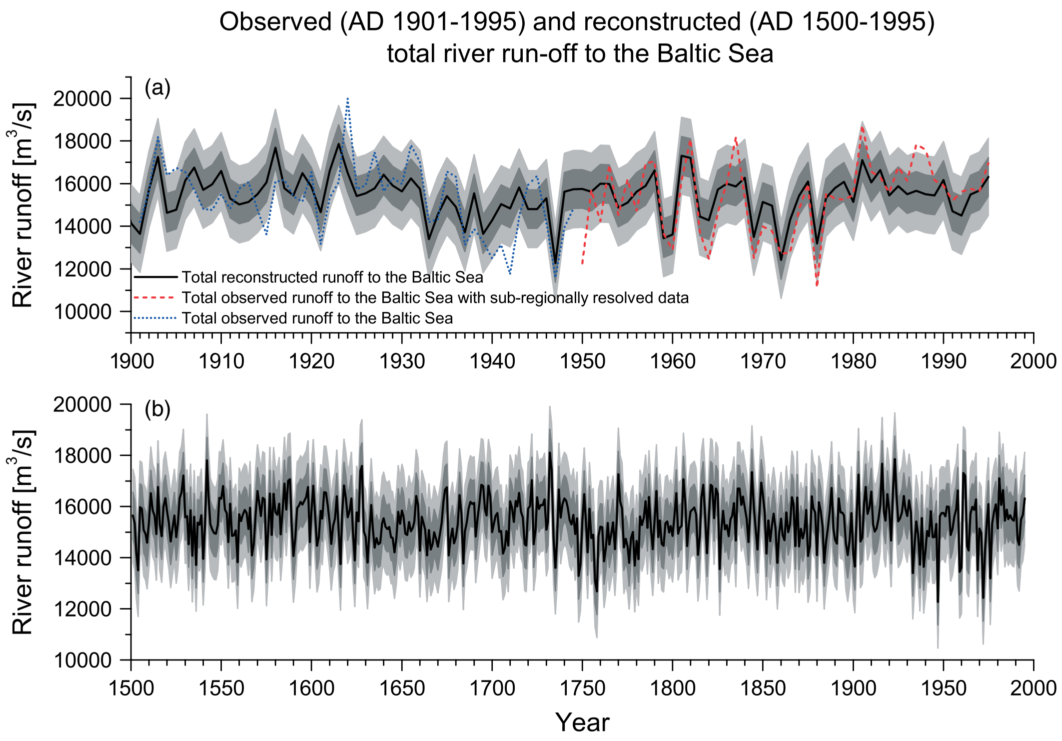

Figure 1. Reconstructed (black line) and observed (blue and red line) annual river runoff over the 20th century (a). For the 1901–1949 period, only data on estimated total runoff to the Baltic Sea are available (blue line). From 1950 and onwards, observations from all three sub-regions are available (red line). (b) The full reconstructed annual river runoff to the Baltic Sea over the 1500–1995 period is seen. The grey shading indicates 1 and 2 standard errors of the reconstructed river runoff. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

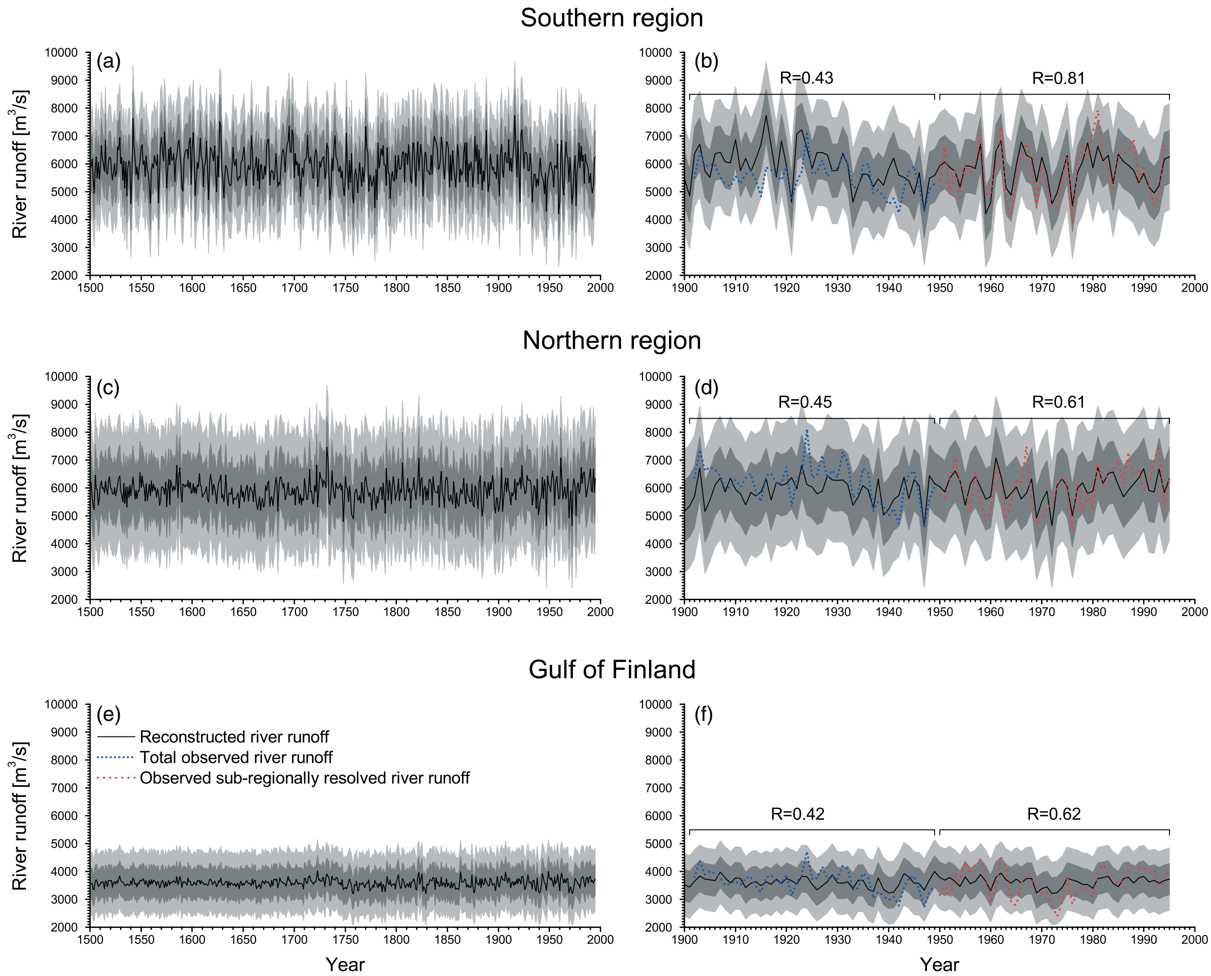

Figure 2. Reconstructed annual river runoff (black line) with the 10-year moving average (magenta line) over the 1500–1995 period for the southern region (a), northern region (c), and Gulf of Finland (e). Observations of freshwater discharge (blue and red lines) in comparison with model results are shown for the southern region (b), northern region (d) and Gulf of Finland (f). The grey shading indicates 1 and 2 standard errors of the reconstructed river runoff. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

Wróblewski, 2000). No statistically significant trend can be found over the full reconstructed period. The 20th century began with above-average river runoff and slipped into a dry period lasting from the early 1930s to the late 1970s, after which a wet period began. A similar pattern is observed in the 18th century, where the driest period since 1500 occurred between the 1740s and mid-1780s.

Changes on sub-regional scale are quite noticeable (Figure 2). In the southern region, runoff changed rapidly over the 20th century, moving from wet conditions in the 1910s and 1920s, to drier conditions in the late 1930s and 1940s (Figure 2(a) and (b)). Since the 1930s, freshwater discharge has generally been lower than the long-term average of the past 500 years. The overall wettest period occurred in the 1690s, also coinciding with the coldest period in the region (Hansson and Omstedt, 2008). There has been a small but insignificant decreasing trend over the past 500 years in the southern region. The model is skilful over the calibration period, with a correlation coefficient of 0.81 ± 0.04; over the validation period, however, this falls to 0.43 ± 0.11 (Figure 2(b)) but remains significant. In the northern region, the 20th century was generally wetter than the average of the past 500 years (Figure 2(c) and (d)). The 1980–1995 period was the wettest since the 1720s, and the 20th century was the wettest century since 1500. A small, but insignificant, trend towards increasing freshwater discharge is apparent in the northern region over the past 500 years; the correlation coefficient over the calibration period is 0.61 ± 0.10 but descends to 0.45 ± 0.14 over the validation period (Figure 2(d)). In Gulf of Finland, the 1720s and 1970s were the wettest and driest periods since 1500 (Figure 2(e) and (f)). The second half of the 18th century was unusually dry, while the 20th century was the wettest century. No significant trend is present in the reconstructed series for this region. For the calibration period, the model is skilful at describing the river runoff with a correlation coefficient of 0.62 ± 0.11; this decreases to 0.42 ± 0.12 over the validation period (Figure 2(f)) but remains significant.

The performance of the reconstruction is evaluated using wavelet analysis. This method allows us to examine the variability of the reconstruction and observational data over different time scales (Percival *et al.*, 2004).

A multiple resolution analysis (MRA) based on the maximum overlap discrete wavelet transform (MODWT) was therefore applied on the river runoff data from both time series. MODWT is a decomposition of a time series giving localized coefficients that can be compared with those of other time series to ascertain the correlation structure on a scale-by-scale basis (Karlöf *et al*., 2006). In Figure 3 the wavelet cross-correlation between the observational and modelled runoff data for each wavelet scale are shown together with its confidence interval. It is apparent that the reconstruction captures the variability associated with different wavelet scales, yielding high correlation coefficients. In Figure 4 the MRA for the full period of the reconstructed river runoff is shown together with observations for the past century. The MRA is an additive decomposition, based on the MODWT coefficients that express the original time series as the sum of several new series, each associated with variations on a particular scale. By comparing observations and reconstructed data it is noticeable that the reconstruction is capturing the variability on the different scales. However, the amplitudes associated with the scales corresponding to fourth- and eighth-year averages are somewhat smaller in the reconstruction, resulting in slightly higher amplitude in the 'smooth' ($\tilde{S}_4$) associated with averages of 16 year or longer (see Karlöf *et al*., 2006 for a detailed description of MODWT-based MRA). Variability on different time scales is sustained throughout the reconstructed period, yet somewhat modulated over the centuries.

As the zonal and meridional atmospheric circulation patterns differ over the Baltic Sea drainage basin, different responses could be expected due to different regional air temperatures. This approach is similar to that outlined in Bergström (2007) and Hisdal *et al*. (2007). In Figure 5(a), the reconstructed river runoff for each of the three sub-regions since 1500 is plotted against the regional mean annual temperatures, as used in Hansson and Omstedt (2008). In both the northern region and Gulf of Finland, increased temperature is associated with greater volumes of river runoff, the increase per degree Celsius being 0.5% (70 m^3/s) and 0.2% (35 m^3/s), respectively. In the southern region, increased temperature is related to decreased river runoff, the decrease per degree Celsius being in the order of 3% (470 m^3/s). The lower panel in Figure 5 displays reconstructed total river runoff as a function of temperature. A change of 1 °C results in a decrease of 3% (450 m^3/s). All changes in response to temperature are statistically significant at the 95% level.

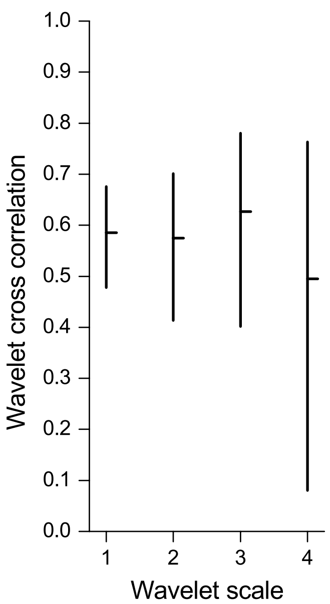

Figure 3. Wavelet cross-correlation at zero lag based upon a Daubechies D(4) wavelet and a maximal overlap discrete wavelet transform (MODWT) using reflection boundary conditions. The correlation between the two series is shown according to their wavelet scale for the 95% confidence interval, with their corresponding upper and lower limit.

4. Discussion and conclusions

We reconstructed the Baltic Sea river runoff from 1500 to 1995 solely based on temperature and general atmospheric circulation patterns. Processes related to soil and vegetation dynamics have not been taken into account. Despite this substantial simplification a great part of the river runoff dynamics can be explained. The temperature and atmospheric circulation indices used are based on datasets that become denser (both spatially and temporally) in climatological information as time progresses. Before the mid-18th century, no direct pressure or temperature observations exist for the Baltic Sea region. However, the Baltic Sea climate varies with the large-scale atmospheric circulation patterns over Europe, which has been reconstructed for the period before the mid-18th century by Luterbacher *et al*. (2002, 2004). Due to the uncertainties associated with our reconstruction, the river runoff data for the 16th and 17th centuries are more uncertain than those for the following centuries. However, as shown by the MRA analysis, the reconstruction retains its variability on all time scales, albeit underestimated on decadal time scales. In addition, we have assumed that the large-scale atmospheric circulation patterns remain stable on time scales larger than seasonal, which may not always be the case. At present this effect is unknown, and thus it introduces further uncertainty in the relationships established in the present paper.

Another uncertainty in our reconstruction is seen in Figure 2(b), (d) and (f), as lower correlation coefficients are scored over the validation period. This does not necessarily mean that the model equations poorly describe the river runoff over this period. Data for observed river runoff before and after 1950 are not directly comparable. From 1950 and onwards, data for river runoff to all parts of the Baltic Sea are available, but before 1950 only data for estimated total observed river runoff to the Baltic Sea are available (Cyberski and Wróblewski, 2000). The absence of historical, highly spatially resolved data unfortunately eliminates region-specific variability and may be

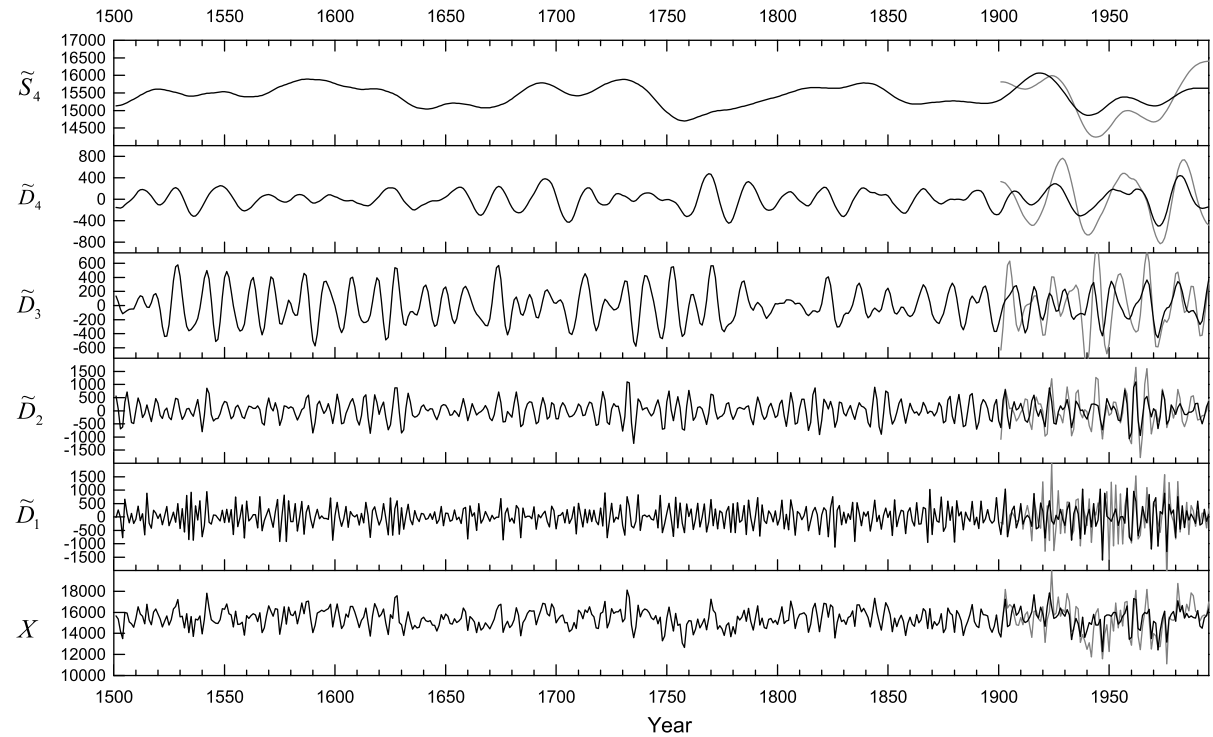

Figure 4. Multiple resolution analysis (MRA) of the reconstructed runoff (black) together with the observed runoff (grey). The MRA is based upon a maximal overlap discrete wavelet transform using a D(4) wavelet with reflection boundary conditions. The bottom panel shows the original time series, above which are the jth detailed series $\tilde{D}_j$ and the smooth series $\tilde{S}_4$. The jth detailed series is based on wavelet coefficients that reflect changes in averages on a scale of 2^{j-1} years, while the smooth series is associated with changes on all scales greater than 16 years.

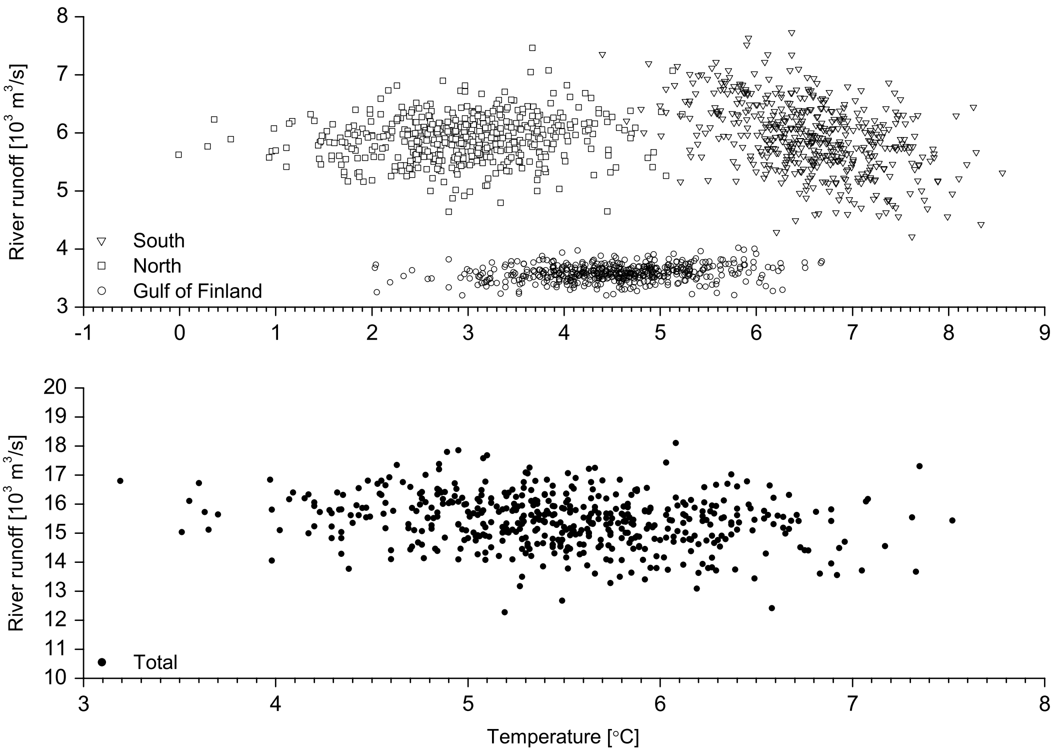

Figure 5. Temperature dependence of the river runoff for the three sub-regions (a) and the total river runoff to the Baltic Sea (b) since AD 1500.

a cause of lower regression scores. Despite this, much of the variability is still captured. When considering the salinity balance of the Baltic Sea, where freshwater discharge is the most important factor, only time scales longer than several decades are significant (Omstedt and Hansson, 2006a, 2006b). The current reconstruction performs well on these time scales as shown by using wavelet analysis. At the same time, lower correlation is also found on annual scales for the whole Baltic Sea river runoff. It is unknown whether this comes from different atmospheric circulation patterns over the first part of the 20th century, or reflects data issues, such as inhomogeneities in the observed data. The problem was also acknowledged in Graham *et al*. (2009). In addition, there has been an extensive expansion of hydroelectric power plants and river regulation, affecting most of the rivers. This has redistributed runoff within seasons.

Large decadal variability has occurred over the past 500 years, though no significant long-term trend was identified in any of the three sub-regions. Despite this, the last decades of the 20th century were among the wettest (in the northern region and the Gulf of Finland) or driest (in the southern region) since 1500, although not exceptionally so. Although anthropogenic climate change is a highly relevant and possible factor in many ways of describing this behaviour, our results suggest that on longer time scales the last decades of the 20th century are not unusual. At least at the present, any clear change in Baltic Sea river runoff is not yet discernable. All regions have at least two seasons when temperature is a predictor in the regression equations. At the same time, climate change may also change the occurrence of the atmospheric indices, e.g. by weakening or strengthening cyclonic systems. It is not yet clear how the general atmospheric circulation on a regional scale will respond to anthropogenic climate change (see e.g. BACC, 2008). Most climate scenarios suggest a general increase in precipitation with increasing temperature. This does not necessarily mean a proportionally increased river runoff. Lindström and Alexandersson (2004) found that there has been an increasing discrepancy between precipitation and river runoff records over the 20th century. This could be explained partly by increased evapotranspiration, but also possible inhomogeneities in observational data. As discussed in Graham *et al.* (2009), an increased evapotranspiration due to increasing temperature may have large effects on runoff in regions where the water surface to land ratio is high, e.g. Gulf of Finland. The projected future total river runoff to the Baltic Sea therefore ranges from a slight reduction to a substantial increase (Graham, 2004; BACC, 2008).

To determine what the future may bring, historical data must be evaluated. In Figure 5, we plotted modelled river runoff against observed annual air temperatures. Comparison of the response of river runoff over time with the projections from BACC provides a good benchmark for testing the present results. Our results show that increasing temperatures over the past 500 years has resulted in more river runoff in the northern and eastern Baltic Sea. According to BACC, Gulf of Finland and the northern region will most likely experience more annual river runoff over the 2071–2100 period than over the 1961–1990 period (see their Figure 3.34), thus indicating a preserved response to temperature in the north. In the south, the river runoff in a warmer climate has been associated with drier conditions and less river runoff, which also is in accordance to future projections in BACC. In addition, there are large uncertainties in modelled future annual runoff for the Baltic Sea, ranging from a reduction to an increase. Our results suggest that the Baltic Sea as a whole would receive less freshwater via rivers if the region continues to warm. If the response in runoff to temperature remains the same in the future as it has been over the past 500 years, the expected decrease in total annual runoff is 3% per degree Celsius. According to BACC, the projected increase in average annual temperatures in the Baltic Sea region is 3–5 °C over the 21st century. Assuming a linear and stationary relationship, our results would imply a reduction of 8–14% (1300–2200 m^3/s) from the average runoff levels of the present. The projected river runoff for 2100 would therefore range from approximately 13 200 to 14 100 m^3/s, albeit associated with large uncertainties. In line with the results of Omstedt and Hansson (2006a, 2006b), the increase in salinity in the Baltic Sea would be 2–3 PSU. In a model study by Meier *et al*. (2006) the future salinity may range between a 4% increase and a 45% decrease. The main difference is that the present study uses observational and reconstructed data, while Meier *et al*. (2006) uses a regional climate model. The divergence between this and other studies shows the need for more research to uncover the future dynamics in runoff, e.g. impacts on vegetation growth. Due to large uncertainties in projected river runoff, even larger uncertainties are associated with future salinity projections. Limiting these uncertainties is crucial for understanding what effects runoff and changed salinity will have for the ecosystems in the Baltic Sea during climate change.

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