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Key Points:

- The latitudinal gradient in the Baltic Sea surface salinity (SSS) has increased during the last century
- Climate variability of the Baltic Sea water cycle (including SSS) is dominated by low-frequency variations on about 30-year time scale
- The long-term change in SSS gradient can be attributed to increasing river runoff in the northern Baltic Sea drainage area

Supporting Information:

- Supporting Information S1

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Changing Salinity Gradients in the Baltic Sea As a Consequence of Altered Freshwater Budgets

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Abstract Climate change is expected to enhance the hydrological cycle in northern latitudes reducing the salinity in the Baltic Sea, a land-locked marginal sea with a large catchment area located in northern Europe. With the help of ocean simulations forced by historical atmospheric and hydrological reconstructions and local observations, we analyzed long-term changes in the sea surface salinity of the Baltic Sea as well as its latitudinal gradient. The variability of both is dominated by multidecadal oscillations with a period of about 30 years, while both atmospheric variables, wind and river runoff, contribute to this variability. Centennial changes show a statistically significant positive trend in the North-South gradient of sea surface salinity for 1900–2008. This change is mainly attributed to increased river runoff from the northernmost catchment indicating a footprint of the anthropogenic impact on salinity with consequences for the marine ecosystem and species distributions.

1. Introduction

The sea surface salinity (SSS) is an important variable for the marine ecosystem because most species are either adapted to marine or freshwater conditions. Hence, high spatial and temporal variability have high impacts on primary production and fish biomass. Although the Baltic Sea ecosystem is highly productive, it has low biodiversity due to low salinity values.

In the salinity range between 5 and 7 g/kg, the so-called horohalinicum, a minimum number of species, is found, since most species are not specifically adapted to brackish conditions (Vuorinen et al., 2015). In the present climate, the horohalinicum is located in the center of the Baltic Sea and a future freshening due to climate change (Meier et al., 2006) would be an additional threat for halophilic fish populations and other marine species. Indeed, since the 1970s, fish biomass in the Baltic Sea has declined due to the decreasing SSS emphasizing the important role of changes in the regional water cycle for the marine environment (Vuorinen et al., 1998).

The Baltic Sea has often been used as a laboratory for global climate and environmental changes since it is well observed due to long-term marine and land-based monitoring programs (Conley, 2012; Reusch et al., 2018). Following this approach, we analyze long-term salinity records to detect changes in the water cycle in the catchment area. The Baltic Sea is one of the biggest brackish seas in the world with limited exchange with the open sea through the Danish straits. The salinity of the Baltic Sea east of 13°E ranges between 13 g/kg at the bottom in the central Baltic Sea and 2 g/kg at the surface in the Bothnian Bay (cf. Figure 1). The Baltic Sea salinity is driven by freshwater supply due to river runoff and net precipitation and the exchange with saline water from the North Sea. Due to its higher density, new saline water accumulates mainly at the bottom of the Baltic Sea and reaches the surface via vertical advection, entrainment, and turbulent diffusion (BACC Author Team, 2008). Most of the salt is transported into the Baltic Sea during so-called major Baltic inflows (Franck et al., 1987; Mohrholz, 2018). These events happen sporadically, mainly during winter, with a maximum of a few times a year. Since 1887, frequency and intensity of major Baltic inflows did not change systematically although a pronounced multidecadal variability with a main period of 25–30 years was found (Mohrholz, 2018). Hence, long-term changes in salinity are likely driven by changes in wind and river runoff (Meier & Kauker, 2003a). Based on 4-year annual mean values, accumulated freshwater supply by the rivers explains about 50% of the decadal variability of the Baltic Sea mean salinity (Meier & Kauker, 2003a, 2003b; Winsor et al., 2001).

The river flow in northern Europe is well monitored (Stahl et al., 2010) and serves as a good database for detection and attribution studies in a warming climate. Under global warming, an intensification of the

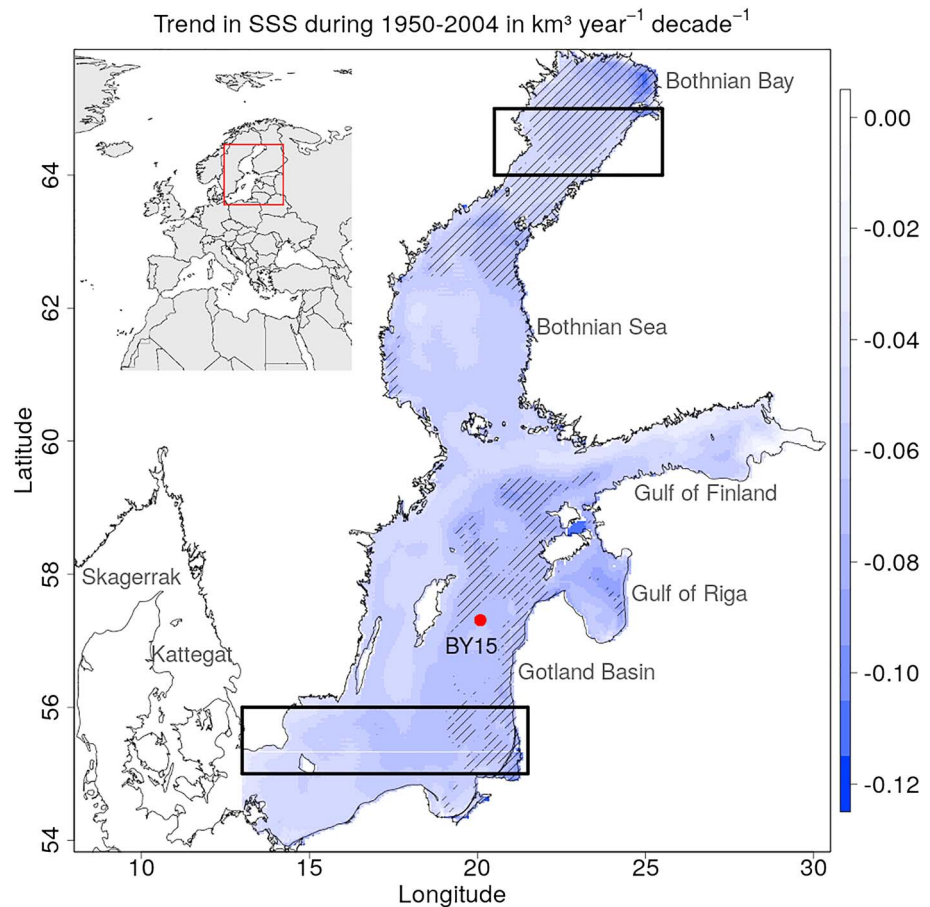


Figure 1. Trends in SSS during 1950–2004 with hatched 95% significance. The two black boxes depict the areas for the North-South gradient calculation, and the station BY15 (Gotland Deep) is the location for the observations representing the Baltic Sea mean salinity anomalies. SSS = sea surface salinity.

global hydrological cycle is projected. Although the total annual mean river flow in the Baltic Sea catchment area was rather stable since 1920, a few rivers showed increasing trends (BACC II Author Team, 2015; Hisdal et al., 2010; Lindström & Bergström, 2004). Since the 1970s, the total winter mean river flow increased and the summer flow decreased, maybe partly because many of the rivers are regulated since the 1970s (Carlsson & Sanner, 1994). However, the observed seasonal changes agree well with future projections under climate change (e.g., Graham, 2004). When averaged over the land areas of the midlatitudes (30°N to 60°N) of the Northern Hemisphere, all data sets of precipitation show an increase in precipitation on 66% probability with medium confidence since 1901 and high confidence after 1951 (IPCC AR5, 2013).

Salinity in the surface layer of the Baltic Sea is well mixed and serves as a low-pass filter of the atmospheric and hydrological forcing, that is, wind, river runoff, and precipitation, indicating long-term changes in regional climate. While long-term trends in salinity observations since the start of measurements in the late nineteenth century are statistically not significant (Fonselius & Valderrama, 2003; Winsor et al., 2001), SSS decreased since the 1970s (Samuelsson, 1996; Vuorinen et al., 1998) although volume-averaged salinities remained unchanged indicating an intensification of the vertical stratification (Meier & Kauker, 2003a).

In this study, long-term variability of SSS since 1900 is investigated and the changes are attributed to changing river runoff and wind over the Baltic Sea basin.

2. Data and Methods

Results of the Rossby Centre Ocean model (Meier et al., 2003) were used to analyze spatially and temporally consistent time series of SSS. Sensitivity experiments were carried out to investigate the role of wind and

river runoff for salinity changes. The circulation model is based on the primitive equations and has a spatial resolution of 3.7 km in the horizontal and 3 m in the vertical dimension.

The model is forced for the period 1850–2008 with the high-resolution atmospheric forcing fields HiResAFF by Schenk and Zorita (2012) which were used before to address long-term climate variability of the Baltic Sea region (Gustafsson et al., 2012; Kniebusch et al., 2019; Meier et al., 2018).

The river runoff in the simulation consists of multiple observational data sets which were merged in order to get a homogeneous river runoff data set (Meier et al., 2018). Reconstructions for 1850–1900 by Hansson et al. (2011), for 1901–1920 by Cyberski et al. (2000), and for 1921–1949 by Mikulski (1986) were used. Observations from the BALTEX Hydrological Data Center (BHDC; Bergström & Carlsson, 1994) were available from 1950 to 1998 and extended and replenished by hydrological model results from Graham (1999). Due to the low quality of the early reconstructions and to avoid discontinuities in interannual and decadal variabilities of river runoff, only the results after 1920 are used. Since Meier et al. (2018) postprocessed the runoff observations of the BHDC, the original data of the period 1950–1998 (Bergström & Carlsson, 1994) are additionally used to verify the results (see supporting information).

In this study, the reference simulation (REF) applying the forcing data as described above and three sensitivity experiments from Meier et al. (2018) affecting the salinity are analyzed. In WIND, the wind fields of the year 1904 are repeatedly applied as forcing. In constrUNOFF, river runoff was set to climatological monthly mean runoff of the period 1850–2008 and in FRESH, the river runoff was increased by 20%, while the relative interannual variability was retained. In all experiments, the annual cycle and the interannual variations of the other atmospheric forcing variables were left unchanged compared to REF.

The model, the sensitivity experiments, and the river runoff data used in this study are thoroughly described and evaluated by Meier et al. (2018). The spatial and temporal comparison with several observational data sets (in situ monitoring data and historical lightship data) revealed that long-term variabilities of temperature and salinity are well reproduced (Kniebusch et al., 2019; Meier et al., 2018).

The study area including important stations and regions is shown in Figure 1. In this study, only the Baltic Sea east of 13°E is considered due to the large spatial gradients in the Danish straits. The latitudinal difference in SSS (hereafter called “gradient”) is expressed as the annual mean North-South salinity difference between the boxes shown in Figure 1. Divided by the distance between the box centers of about 1,000 km, the gradient in our study would refer to a horizontal gradient in $10^{-3} \text{ g} \cdot \text{kg}^{-1} \cdot \text{km}^{-1}$. We investigate the gradient because area-averaged SSS trends are statistically not significant on centennial time scales.

To evaluate the simulated SSS, measurements from ICES Database (2018) are used. Since the availability of data from the first half of the twentieth century is limited in general and in northern areas in particular, available data from large regions (cf. Figure 1) are averaged. For the evaluation of the simulated Baltic Sea mean salinity, measurements from a $2^\circ \times 2^\circ$ grid box around Gotland Deep (BY15) are used since salinity anomalies at this station represent anomalies of the mean salinity averaged over the entire Baltic Sea (Winsor et al., 2001).

We calculated linear trends during different periods from time series of annual mean salinity and river runoff. However, due to a high decadal variability in river runoff and salinity, an estimation of the significance level of these trends is not straightforward. The decadal variability causes a long-range temporal autocorrelation in the records, which needs to be taken into account. Hence, for significance tests the Phase Scrambling Fourier Transform bootstrap method (Theiler & Prichard, 1996) was applied. The method has recently been used for trend analysis in decadal hydrological (Zanchettin et al., 2007) and large-scale circulation patterns (Thejll et al., 2003). The method works as follows: In the first step, the signal (in this case the linear trend) and the noise are separated. In the second step, the noise is Fourier analyzed, and a large ensemble of artificial noise time series is generated by randomizing the Fourier phases but keeping the amplitudes. This means that the surrogate time series have the same autocorrelation properties as the original noise. The artificial noise is added to the signal, and the linear trend estimation is repeated. From this ensemble of trend estimates, which in our case contained 1,000 members, we derived quantiles and used them as *p* values and confidence intervals.

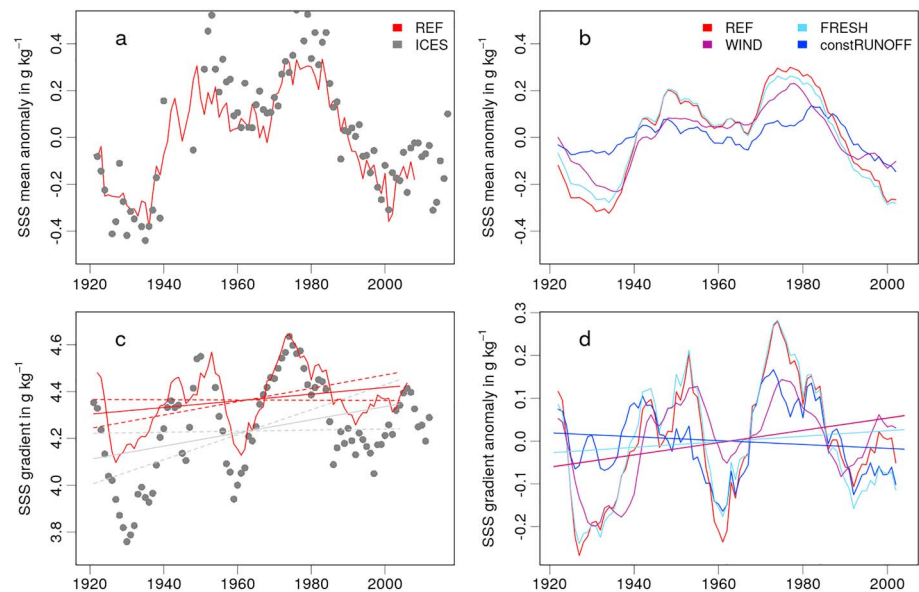


Figure 2. (a) Annual mean and (b–d) 4-year running mean time series of anomalies of the Baltic Sea mean SSS (a and b) and the North-South gradient in the SSS (c and d). (left column) Reference simulation and observations of the ICES database (cf. Figure 1). (right column) Anomalies in the reference simulation and sensitivity experiments. The solid lines in (c) and (d) show the linear trends of the corresponding annual time series. In (b) the 66% confidence intervals of the trends are also shown by the dashed lines. SSS = sea surface salinity; REF = reference simulation; ICES = International Council for the Exploration of the Sea.

3. Results

3.1. Detection of Changes in Salinity

The left column of Figure 2 shows the evolution of the measured and simulated Baltic Sea annual mean SSS anomaly and its low-pass filtered North-South gradient for 1921–2004. The model-observation comparison shows good agreement with correlation coefficients of 0.91 for the mean salinity and 0.77 for the gradient, while the observations in each case show a higher amplitude in the long-term variability.

Figure 2 indicates low-frequency periodic variations with a period of about 30 years in both mean salinity and its gradient, while both are correlated (0.59 in the Rossby Centre Ocean model and 0.61 in observations). Low (high) salinities are accompanied by a small (high) North-South gradient. The negative trend in SSS since the 1970s, which can be seen in Figures 2a and 1 as well as in former publications (Samuelsson, 1996; Vuorinen et al., 1998), seems to be part of the long-term oscillation and is not a systematic change in salinity on centennial time scale. Since the 2000s, the salinity is increasing again. The low-frequency variability with a period of about 30 years can also be seen in the freshwater supply of the model forcing (Meier et al., 2018, their Figure 3).

The trend analysis of the North-South gradient in salinity was done for the period 1921–2004. The observed salinity gradient shows a significant trend (66% confidence) with $0.028 \text{ g} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$, while the simulated gradient increases with $0.014 \text{ g} \cdot \text{kg}^{-1} \cdot \text{decade}^{-1}$ and is not significant. However, considering a longer period, for example, until 2006, when the last peak of the low-frequency oscillation is reached, the trend becomes significant at the 66% confidence level, too. Considering the period 1900–2008, the simulated trend becomes significant at 90% confidence. Since the drift toward a higher gradient can also be seen in the observations, we conclude that this result is not a model artifact; hence, we will investigate the causes of an increasing North-South gradient in SSS with time.

3.2. Attribution to Atmospheric Forcing

The salinity of the Baltic Sea and thus its North-South gradient is mainly dependent on the two atmospheric forcing variables wind (driving the water exchange with the North Sea) and freshwater supply. On long-term, river runoff and net precipitation are considerably correlated (Meier & Kauker, 2003a). Hence, it is sufficient to examine runoff only to attribute long-term salinity changes since the total runoff ($14,000 \text{ m}^3/\text{s}$) is much higher than the total net precipitation (precipitation-evaporation = $1,000 \dots 2,000 \text{ m}^3/\text{s}$) for the whole Baltic Sea area (Meier & Kauker, 2003a; Meier et al., 2018).

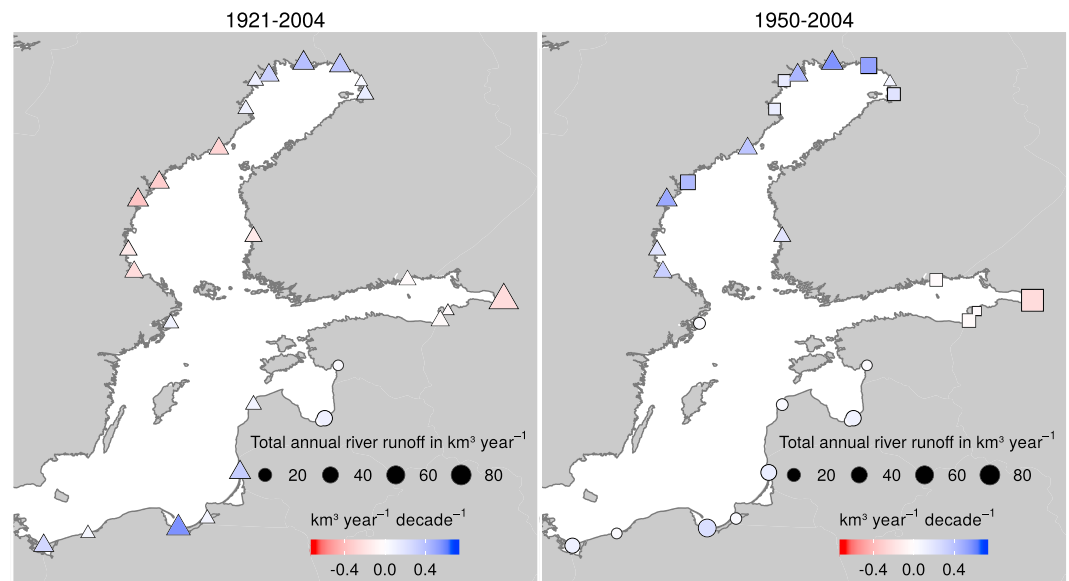


Figure 3. Annual river runoff trends during 1921–2004 (left) and 1950–2004 (right) in cubic kilometers per year per decade. The size of the symbols refers to the total annual river runoff of the corresponding river in the corresponding time period, and the shape refers to the significance (circle—not significant, triangle—66%, and square—90%).

The right column in Figure 2 shows the anomalies in SSS (b) and the gradient (d) for the simulations REF, WIND, constRUNOFF, and FRESH. In all simulations, the low-frequency oscillations of both SSS and the gradient are evident. However, the amplitudes of the oscillations are smaller in both WIND and constRUNOFF, while constRUNOFF explains 66% (67%) and WIND 54% (86%) of the variance in the annual mean gradient (SSS) in the reference simulation. The variance of the gradient in REF amounts to $0.027 \text{ g}^2/\text{kg}^2$. In the sensitivity simulations constRUNOFF and WIND, the variance is much lower with 0.013 and $0.01 \text{ g}^2/\text{kg}^2$; for the SSS anomaly the differences are even larger. In contrast, FRESH reproduces the long-term variability of the SSS anomaly and gradient very well.

The trend estimates of the SSS gradient show substantially different results in the sensitivity experiments. WIND shows about the same trend as REF, while the trend is smaller in FRESH and even negative in constRUNOFF. Hence, river runoff is crucial for the drift in the North-South gradient in Figure 2c.

Since there was no significant change in the annual freshwater supply to the Baltic Sea during 1902–1998 (Meier & Kauker, 2003a), the spatial distribution of trends in total annual river runoff (hereafter called “annual runoff”) for two periods is shown in Figure 3. Both periods show spatially differing trends in annual runoff. During 1921–2004, there is significantly increasing river runoff in southeastern and most northern areas and negative trends in the Bothnian Sea and the Gulf of Finland. During 1950–2004, positive trends spread from the Bothnian Bay to the Bothnian Sea following long-term trends in precipitation patterns (BACC Author Team, 2008). Trends in the Gulf of Finland and in the southern Baltic Sea are negative or around zero and not significant, respectively.

In Figure 1, the simulated trends in SSS are shown for the period 1950–2004. It can be seen that significant changes in the SSS can be found in the northern areas and the eastern Gotland Basin. In the northernmost areas of the Bothnian Bay, where the highest increase in annual runoff was found, the highest changes in SSS are located causing the drift toward a higher gradient in salinity.

4. Discussion

4.1. Long-Term Trends in Salinity, Its Gradient, and the River Runoff

The underlying mechanism of the increasing North-South gradient is complex. The Baltic Sea mean SSS was increasing during 1921–2004 (cf. Figure 2), though not significantly. In this manner, also, the gradient increased since they are correlated directly. Since the amplitude of the variability is small in the northern (fresher) basins, the variability and amount of the gradient are dominated by the SSS in the southern (salty) regions. In contrast, the sensitivity experiments show that the trend in the gradient is independent from

wind, that is, the salt inflows and thus the SSS variability in the South. Hence, it is important to discuss how river runoff causes the increasing latitudinal gradient on centennial time scales. During 1921–2004, there were local significant positive trends in the river runoff in the North. At the same time, the positive trends in SSS in the northern basins were 3 times smaller than those in the South (not shown). In this manner, the locally changing river runoff dominated the centennial trends in the North–South gradient, although the multidecadal variability is dominated by SSS variability in the South.

Increasing river runoff in the northern basins can either be caused by increasing precipitation or the melting of glaciers in the catchment area due to higher temperatures. However, the total volume of Swedish glaciers is rather small and has no impact on the river runoff (Bergström, 1993). In contrast to this, precipitation trends could explain increasing river runoff (Stahl et al., 2010). In Sweden, total precipitation has increased continuously since measurements started in 1860 (Alexandersson, 2002, 2004; Hellström & Lindström, 2008), which may have caused the increased river runoff in the northern basins (cf. Figure 3). However, precipitation trends in Sweden are likely influenced by the increase in the number of measurements (Hellström & Lindström, 2008). Nevertheless, precipitation is expected to increase in higher latitudes with climate change which is consistent with patterns in recent runoff trends (Stahl et al., 2010).

In contrast to the river runoff, the long-term positive trends in salinity during the past contradicts future projections of the Baltic Sea which show a freshening of the Baltic Sea until the end of the 21st century (Meier et al., 2006). This can have several reasons. On the one hand, the inflow statistics in the future simulations might not be correct leading to an underestimation of saltwater inflows. For instance, most available scenario simulations do not consider the global mean sea level rise (Meier et al., 2019). On the other hand, the projected runoff trends in the North may be high enough to turn the small positive trends in SSS toward negative values. In fact, FRESH in Figure 2b already shows a lower trend in SSS than REF and WIND supporting this assumption. However, there could also be internal variability on longer time scales longer than 160 years.

4.2. Causes of the 30-Year Variability

In addition to the Baltic Sea mean SSS and the gradient, the pronounced variability with a time scale of about 30 years is found in precipitation at selected stations (e.g., BACC II Author Team, 2015, their Figure 5.8) or averaged over Sweden (e.g., Hellström & Lindström, 2008, their Figure 3), total river runoff in the Baltic Sea basin (e.g., Meier & Kauker, 2003a, their Figure 3), barotropic saltwater inflows (Mohrholz, 2018, his Figure 3), and volume mean salinity of the Baltic Sea (e.g., Winsor et al., 2001, their Figure 15; Meier & Kauker, 2003a, their Figure 8). Also, wind has a variability on the multidecadal time scale (e.g., BACC II Author Team, 2015).

Barotropic saltwater inflows contribute approximately half to the total salt import into the Baltic Sea (Mohrholz, 2018). According to measurements, changes in Skagerrak deep water salinity are small and likely not a source of long-term changes in Baltic Sea salinity (not shown). Moreover, sensitivity experiments showed that surface layer salinity at the open boundary in Kattegat is not important for saltwater dynamics of the Baltic Sea (Meier & Kauker, 2003b). In this manner, the causes for the multidecadal variability lie either in the wind conditions or the river runoff. The results of the sensitivity experiments indicate that both variables contribute to the multidecadal variability of the Baltic Sea salinity.

The variability in wind and river runoff is mainly explained by variations in large-scale circulation patterns (Hansson et al., 2011; Meier & Kauker, 2003a) which are highly correlated with large-scale climate variability indices like the North Atlantic Oscillation (Hurrell et al., 2003) and the Atlantic Multidecadal Oscillation (Knight et al., 2006). Changes in precipitation over the Baltic Sea basin are caused by atmospheric circulation changes (BACC II Author Team, 2015). Hence, multidecadal variations of the large-scale atmospheric circulation would explain the multidecadal variations in salinity (cf. Börgel et al., 2018). However, neither the Atlantic Multidecadal Oscillation (periods of 60–90 years) nor the North Atlantic Oscillation (subdecadal variability) show a periodicity of about 30 years. Frankcombe et al. (2010) assumed that the 20- to 30-year cycles are induced by the internal variability of the Atlantic Meridional Overturning Circulation. Furthermore, the Scandinavian pattern (originally Eurasian pattern in Barnston and Livezey (1987)) could explain

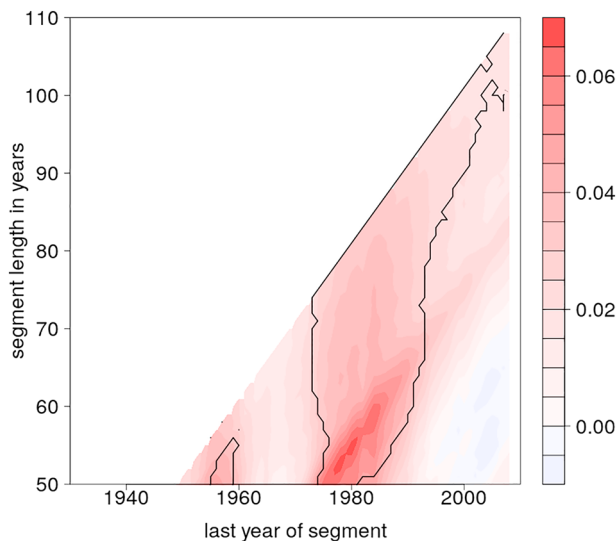


Figure 4. Trend of the simulated North-South gradient in sea surface salinity (cf. Figure 2) in grams per kilogram per decade as a function of the length of the time segment and ending year of the calculation period. The minimum segment length is 50 years due to the low-frequency variability. Areas within the black line are statistically significant at 90% confidence.

the low-frequency oscillations as well. To find out where the internal variability originates will be part of further research.

4.3. Uncertainties

Since the time series is relatively short compared to the time scales of the high multidecadal variability, the significance of trend in the gradient during 1921–2004 is only likely (66% confidence). However, the salinity gradient since 1900 increased on 90% confidence, which is a common level of significance for changes in precipitation (IPCC AR4, 2007; IPCC AR5, 2013). Trends in precipitation and thus freshwater budgets in general are less confident than changes in temperature at the same time, which is why 66% (likely) and 90% (very likely) confidence intervals are often used. The fact that the trend in the North-South gradient becomes more significant with longer time series supports our finding. Figure 4 shows the trends of the gradient in the reference simulation in all periods longer than 50 years following Liebmann et al. (2010). Among them, 80% are positive and 50% significant at 90% confidence. The few slightly negative trends were found after 1970, when the low-frequency oscillation of the salinity turned from its maximum to its minimum. In this manner, although the significance for the considered time period is low, the changes are systematic on long-term perspectives.

Sources of uncertainty mainly arise from the database of the river discharges. As a homogeneous data set for the entire period 1850–2008 does not exist, the model forcing is a combination of several different runoff

data sets (Meier et al., 2018) leading to possible inhomogeneities. To narrow this uncertainty, only simulation results after 1921 are used (two data sets for river runoff) and results are compared to the period with a consistent observational data set (1950–2004). Additionally, the original river runoff data from the BHDC without preprocessing were analyzed in the supporting information. The trend estimates for the five biggest rivers of the northern Baltic Sea during 1950–1997 of the original data set by the BHDC and the postprocessed forcing data are presented and compared. Though the trends differ in amount and significance, all trends are positive leading to a higher freshwater supply in the Bothnian Sea and the Bothnian Bay. An impact of river regulation is also possible, although hydrological model results suggest that after the regulation of many of the large rivers in the 1970s in northern Scandinavia the annual mean runoff of Swedish rivers did not change significantly compared to the period before the 1970s (Carlsson & Sanner, 1994).

Another uncertainty might be caused by the choice of the location of the northern and southern areas for the calculation of the latitudinal gradient. Especially the observations are very sensitive to the choice of the considered area. The definition of the areas in Figure 1 represents a compromise between sufficiently many continuous observations (which would not be the case in the most northern part of the Bothnian Bay) and the location close to the big rivers in the North to get the full range of the salinity difference. Following Fonselius and Valderrama (2003), measurements from different seasons were used for addressing long-term variability of salinity in the Baltic Sea. However, the long-term trend is small compared to the seasonal variability in the southern Baltic Sea. Hence, the higher trend in the observed North-South gradient compared to the simulated trend might be caused by temporally increasing observations in the North. Nevertheless, changing the areas and seasons for the calculation of the simulated North-South gradient did not change the trend estimation considerably (not shown). Moreover, after 1950 observations from almost every month in every year were available. Considering only observations from the most frequently observed month (July) did not change the results either.

5. Conclusions

Low-frequency oscillations with a period of about 30 years dominate the variability of the Baltic Sea salinity since 1850. The short-term trend in SSS since the 1970s is mainly explained by this variability. Sensitivity experiments showed that the low-frequency oscillations in SSS were caused by corresponding oscillations in both runoff and wind. The low-frequency variability in SSS is also well correlated with the North-South gradient in SSS.

There is a significant long-term trend in the SSS gradient during 1900–2004 (90% confidence). Our sensitivity simulations revealed that this trend will vanish if the annual mean river runoff is kept constant, indicating that the increase in SSS gradient is caused by local changes in river runoff. A detailed analysis of long-term trends in river runoff showed that at least since 1921, freshwater fluxes in the Bothnian Bay, the northernmost Baltic Sea basin, have increased. Positive runoff trends spread southward and include the rivers of the Bothnian Sea during 1950–2004.

In summary, the SSS in the Baltic Sea was increasing during the last 100 years, though the multidecadal variability caused by large-scale precipitation and wind fields prevented any significance. Since the North-South gradient is dominated by the more saline and variable southern regions, it increased with increasing SSS, too. However, the regionally increasing river runoff in the northern basins additionally increases the difference between North and South leading to a significant positive trend on centennial time scales.

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