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Multidecadal climate variability dominated past trends in the water balance of the Baltic Sea watershed

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The Baltic Sea watershed includes the territories of 14 countries in Northern, Central, and Eastern Europe. Long-term observations have shown that the climate in this area is characterised by a pronounced multidecadal variability, with a period of about 30 years, but its origin is thus far unknown. We propose that the observed ~30-year fluctuations in Baltic Sea salinity are caused by the Atlantic Multidecadal Variability and the North Atlantic Oscillation, which together modulate precipitation over the watershed and hence the river discharge into the Baltic Sea. The return of a large portion of the outflowing brackish Baltic Sea water with the inflowing salt water, due to mixing at the entrance area results in a positive feedback mechanism that amplifies the multidecadal variations in salinity. The strength of this self-amplification is considerable since atmospheric forcing has nearly the same periodicity as the response time of the freshwater content to external freshwater inputs.

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INTRODUCTION

The footprint of anthropogenic warming has been detected in many variables of the energy cycle, even at a regional scale¹. In Northern Europe, the warming associated with climate change significantly affects the cryosphere (snow, sea ice, lake ice, river ice and glaciers), whereas systematic changes in water cycle variables (precipitation, evaporation, river discharge, ocean salinity) are less obvious¹. In the early 1990s, the global water and energy exchanges (GEWEX) project, as part of the World Climate Research Programme, recognised the Baltic Sea catchment area as one of the regions on Earth where changes in the water cycle could be quantified². This region was singled out because the salinity of the semi-enclosed Baltic Sea depends on the freshwater supply (Supplementary Fig. 1a) from a catchment area that is about four times as large as the Baltic Sea surface (Fig. 1). As the salinity of the Baltic Sea and water exchange between the Baltic Sea and the adjacent North Sea (the latter estimated from sea level records within and outside the Baltic Sea) have been monitored since the 19th century (Supplementary Fig. 2), the Baltic Sea region is well-suited to studies of the regional water cycle, using salinity as a proxy for changes in precipitation and evaporation in the entire catchment area^{2–4}.

Rather than a systematic trend, the mean salinity of the Baltic Sea is characterised by a pronounced low-frequency variability with a period of about 30 years, at least since 1920 (Supplementary Fig. 3). This variability has been documented in long-term observations^{5–8} and historical, model-based reconstructions^{8–11}. A similar multidecadal variability describes the total river discharge from the Baltic Sea catchment area⁹ (see also Supplementary Fig. 4), individual river flows¹², barotropic saltwater inflows across the sills located in the Baltic Sea entrance area¹³ (see also Supplementary Fig. 5), water temperature¹⁴, sea level¹⁵, and atmospheric variables such as precipitation and the winds over the Baltic Sea region⁹. Centennial changes have been determined as well, including a positive trend along the north-south gradient of sea surface salinity (SSS) for the period 1900–2008⁸. However,

neither the trends in mean salinity^{6–9} nor those at selected monitoring stations¹⁶ were statistically significant.

Recent studies suggest that the Atlantic Multidecadal Variability (AMV) contributes to the observed low-frequency variability of the Baltic Sea basin^{17,18} and other regions in the Northern Hemisphere, such as the Arctic Ocean¹⁹. The AMV is defined as the low-frequency variability, with alternating anomalous warm and cold states, that characterises the annual mean, spatially averaged sea surface temperature (SST) in the North Atlantic²⁰. For the period 950–1800, Börgel et al.¹⁸ traced the AMV signal determined in a regionalised paleoclimate simulation of the last millennium²¹ to the Baltic Sea region. The AMV, with a currently observed period of 60–90 years^{22–24}, likely affected the water temperature in the Baltic Sea and partly explained the stronger increase in the mean SST of the Baltic Sea¹⁴ than of other coastal seas worldwide²⁵ as determined since the 1980s.

In mid and high northern latitudes, the most prominent pattern of climate variability is the North Atlantic Oscillation (NAO), which strongly influences the weather over northeastern North America, Greenland, and Europe during winter at time scales of about 4–10 years²⁶ and controls the strength and direction of westerly winds across the North Atlantic region. The NAO index is defined as the difference in atmospheric pressure at sea level between the Icelandic Low and the Azores High. Several studies have shown a mutual causal influence of the AMV and NAO^{27–32}. For example, Börgel et al.¹⁷ found that the AMV causes changes in the zonal position of the NAO's centres of action over time. During a positive AMV, the Icelandic Low moves further towards North America, and the Azores High further toward Europe, with the opposite occurring during a negative AMV¹⁷. As a consequence of the shifting centres of action, the correlations between the NAO and variables characterising the Northern European climate, such as water temperature, sea ice, and river discharge, vary in time¹⁷.

In this study, with the aid of historical, model-based ocean reconstructions and sensitivity experiments, we provide an explanation for the origin and mechanisms of the low-frequency variability in Baltic Sea salinity and in other variables that show a

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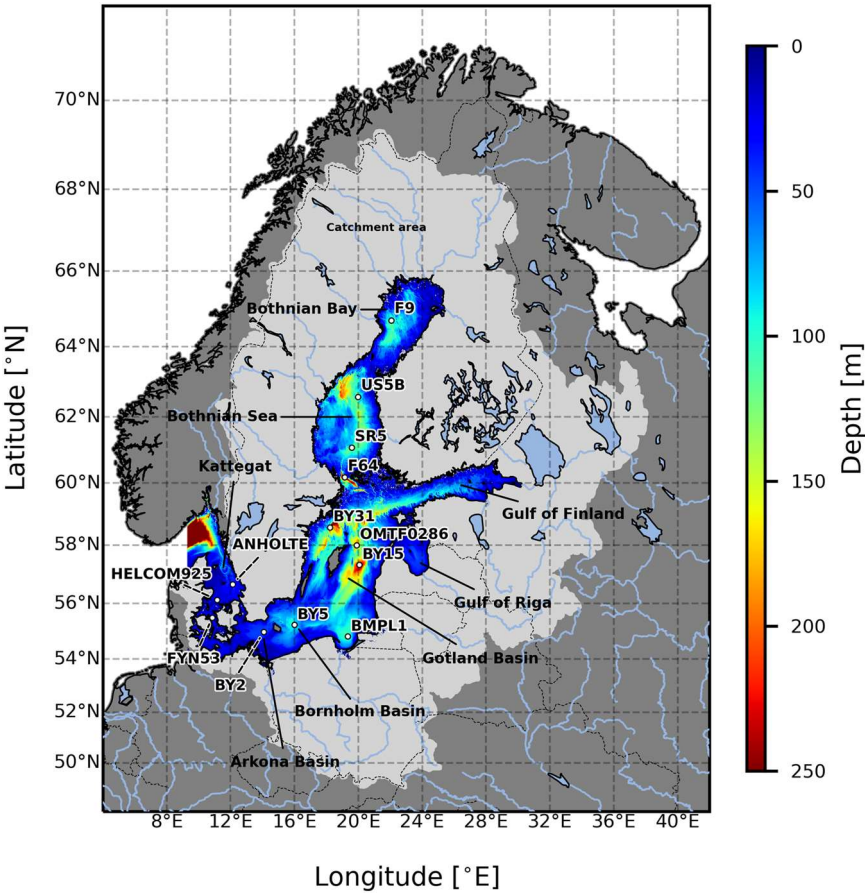


Fig. 1 Baltic Sea bathymetry. Water depth (in m)⁶⁰ and the locations of the long-term monitoring stations are shown. The domain of the Baltic Sea model is limited, with open boundaries in the northern Kattegat. The main sub-basin of the central Baltic Sea is the Gotland Basin.

Table 1. Numerical experiments.			
Experiment	Description	Relative sea level rise	Average salinity 1900–2005
1 REF+	Reference run with a sea level rise	1 mm year ^{−1} ⁴⁰	7.72 g kg ^{−1}
2 REF	Reference	0	7.60 g kg ^{−1}
3 RUNOFF+	Climatological mean river discharge and constant net precipitation of 2364 m ³ s ^{−1} ⁶² , sea level rise is considered	1 mm year ^{−1} ⁴⁰	7.61 g kg ^{−1}
4 RUNOFF	As RUNOFF+ but without sea level rise	0	7.49 g kg ^{−1}
5 WIND	As RUNOFF but with the repeated wind of the year 1904	0	5.82 g kg ^{−1} (7.49 g kg ^{−1} with drift correction)

period of about 30 years. For the period 1850–2008, five numerical simulations were performed, including a reference run (REF+), a sensitivity experiment that included the climatological mean freshwater supply (RUNOFF+), and both runs in which the global sea level rise (SLR) was excluded (REF and RUNOFF). Finally, a sensitivity experiment (WIND) was carried out that was identical to RUNOFF but with repeated wind fields for the year 1904 (Table 1).

We argue that the AMV is the pacemaker of the variability of the moisture transport from the North Atlantic to Northern Europe, as it periodically shifts the centres of action of the NAO with a current period of about 60 years. Hence, Northern Europe is alternately under the stronger and weaker influence of the milder, wetter North Atlantic climate. As the NAO and AMV influence Northern Europe, the combination of their respective patterns affects the annual mean precipitation over the Baltic Sea catchment area, river discharge, and the sea level in the Baltic Sea for a period of about 30 years. Consequently, salinity in the Baltic Sea oscillates

with the same periodicity due to direct dilution. However, the latter oscillation is considerably amplified because, in addition to dilution, saltwater inflows are less (more) saline during decades with increasing (decreasing) accumulated freshwater input. Due to this self-amplification, by monitoring Baltic Sea salinity, large-scale changes in the Northern Hemisphere water cycle can be detected, thereby furthering the aims of the global GEWEX project.

Our findings are also significant with respect to ecosystem functions and structure. Changes in salinity significantly affect the marine ecosystem because many species are adapted to specific salinity ranges, including the freshwater to marine conditions of the Baltic Sea^{33–35}. This study traces the origin of natural variations in salinity on multidecadal time scales. With our results, the trends caused by climate change could be separated from natural variations. Although this goal has not yet been fully achieved, decadal climate predictions for salinity may soon become possible. Such predictions could aid sustainable ecosystem

management, including the planning of fishing quotas. For instance, the reduction in weight of 3-year-old central Baltic Sea herring (*Clupea harengus*) from the late 1970s until today has been attributed to the declining salinity resulting from the multidecadal variability, which has also led to a reduction of fish catches and thus an estimated economic loss of roughly €100 million³⁶. If the decline in salinity in this or other cases had been known in time, fisheries management could have reacted to the changed environmental conditions for the fish and adjusted catch quotas, and possibly an economic loss could have been avoided.

RESULTS

The origin of the low-frequency variability in the Baltic Sea

During periods with a positive winter NAO index, the winter climate over Northern Europe is warmer and wetter, and the volume of river flow from the Baltic Sea catchment area is larger compared to the long-term mean (Fig. 2). Due to the lateral displacement of the centres of action of the NAO, in particular the Icelandic Low, the AMV affects both the location of the storm track over Northern Europe and the winter NAO index in the period band of >60 years (Fig. 3). Although this power band lies just outside the cone of influence of the wavelet power spectrum of the NAO, due to the relatively short time series since 1825³⁷ (not shown), we argue that the combination of the zonal displacement of the NAO centres and the AMV is largely responsible for the multidecadal variability of the atmospheric flow over Northern Europe. Moreover, as the temperature fluctuations related to AMV variability and the movement of the NAO centres of action have the same periodicity, the resulting signal contains the square of the AMV harmonic with a period of about 30 years. Otherwise, the impact of the interference on the NAO is relatively small (Fig. 3). Thus, the dominating wavelet power of the NAO is situated within a period band of 4–10 years and within an AMV period band of >60 years, as expected (Fig. 3). Our hypothesis, that the AMV accounts for the 30-year climate variability over Northern Europe, is supported by the relatively high wavelet coherence of the squared AMV and the winter mean zonal wind over the central Baltic Sea in that period band (not shown). However, a confirmation of our hypothesis is difficult as the observed and reconstructed time series are relatively short compared to the dominating long-time scales of the AMV. A more detailed analysis of regional climate variability, for instance, in paleoclimate simulations and their dependencies on the AMV remains for future research.

Winter precipitation over Northern Europe, mainly explained by the advection of humid air masses from the Atlantic, therefore has a pronounced low-frequency variability of about 30 years, the phase of which corresponds well with the atmospheric flow field

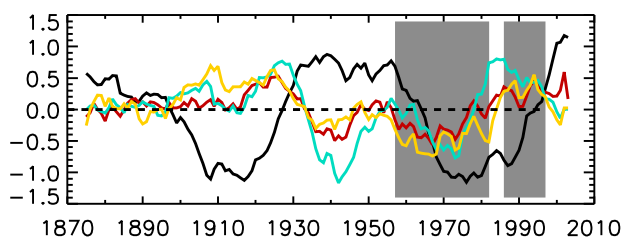


Fig. 2 Atlantic Multidecadal Variability (AMV) index, North Atlantic Oscillation (NAO) index, precipitation averaged over the Baltic Sea catchment area, and total river discharge. Low-pass filtered AMV (black)⁵⁹, precipitation⁵² (red), river discharge¹⁰ (cyan), and the winter (December through February) NAO index³⁷ (orange), with a cut-off frequency of 12 years. All records were normalised by their standard deviations. Selected recent periods with predominantly low (1957–1982) and high (1986–1997) NAO indices are shown as grey-shaded areas.

over the region (Fig. 2). A calculation of the Pearson correlation coefficients between the low-pass filtered precipitation or river discharge and the winter NAO index with a cut-off period of 12 years (shown in Fig. 3) yielded a value of 0.76 or 0.58. Moreover, the correlation between precipitation and river discharge was similarly high (0.79), in accordance with an earlier study³⁸. Hence, river discharge is subject to multidecadal variations within the same period of about 30 years and with an amplitude of about 7% of the total mean river discharge of about $14,000 \text{ m}^3 \text{ s}^{-1}$ (Supplementary Figs. 1 and 4).

In the following, we analyse a set of sensitivity studies aimed at disentangling the contributions of the different physical drivers to the low-frequency variability of the Baltic Sea's salinity. In general, salinity in estuaries is controlled by the freshwater supply from rivers of the catchment area and precipitation minus evaporation over the sea, saltwater inflows from the open ocean, and mixing by tides and wind fields.

In the Baltic Sea, the large annual freshwater supply, comprising about 2.3% of the sea's total volume, causes a large horizontal gradient in salinity of about 20 g kg^{-1} between the entrance area and the eastern- and northern-most parts of the Baltic Sea. To examine the impact of multidecadal freshwater input variations on salinity, we performed a sensitivity experiment (RUNOFF+) based on the climatological mean freshwater input (Table 1). As the Baltic Sea is semi-enclosed, with limited water exchange with the world ocean through narrow and shallow straits (Fig. 1), wind-driven large saltwater inflows, so-called major Baltic inflows (MBIs), occur only sporadically, but they are essential for the ventilation of Baltic Sea's deep water¹³. The intensity of saltwater inflows will probably increase as the global sea level rises because, in a first approximation, the transport is proportional to the cross-section at the sills³⁹. Using the sensitivity experiments REF and RUNOFF without the global SLR, we investigated whether the SLR is responsible for the observed trends in the recent evolution of salinity. As the zonal west wind may hamper the outflow of brackish water from the Baltic Sea and thus limit the inflow of saltwater, an additional experiment with a constant wind was performed (WIND). Unlike in many other estuaries, in the Baltic Sea, the tides are small and low-frequency wind-induced mixing does not affect the temporal evolution of the mean salinity¹¹.

Impact of the freshwater supply on salinity

In the two model simulations with and without SLR (REF+ and REF), the mean salinity during 1900–2005 was 7.72 and 7.60 g kg^{-1} , respectively (Table 1). The analysis was limited to the period 1900–2005 because the reconstructed river discharge before 1900 is less reliable. The difference in mean salinity reflects the effect of the SLR relative to the sea bottom on the overall salinity in the Baltic Sea. Similar values were obtained in the two sensitivity experiments focusing on climatological freshwater input with and without SLR (RUNOFF+ and RUNOFF). The applied SLR of 1 mm year^{-1} or 10.6 cm during 1900–2005 relative to the sea bottom at the sills in the Baltic Sea entrance area⁴⁰ corresponded to a salinity increase of 0.12 g kg^{-1} or $+1.13 \text{ g kg}^{-1} \text{ m}^{-1}$, which was somewhat smaller than the value obtained in a study by Meier et al.³⁹, in which the average salinity change per SLR was $+1.41 \text{ g kg}^{-1} \text{ m}^{-1}$. The difference can be explained by the temporal evolution of the SLR, i.e., a linear vs. step-function-like increase, as in Meier et al.³⁹, and the different study periods.

The results of the sensitivity experiment RUNOFF+ suggested that the interannual variations in the total freshwater supply alone explained about 52% of the Baltic Sea's interannual mean salinity variations determined in REF+ for periods >12 years (Fig. 4). The standard deviations in RUNOFF+ amounted to 0.1 g kg^{-1} , compared with 0.2 g kg^{-1} in REF+.

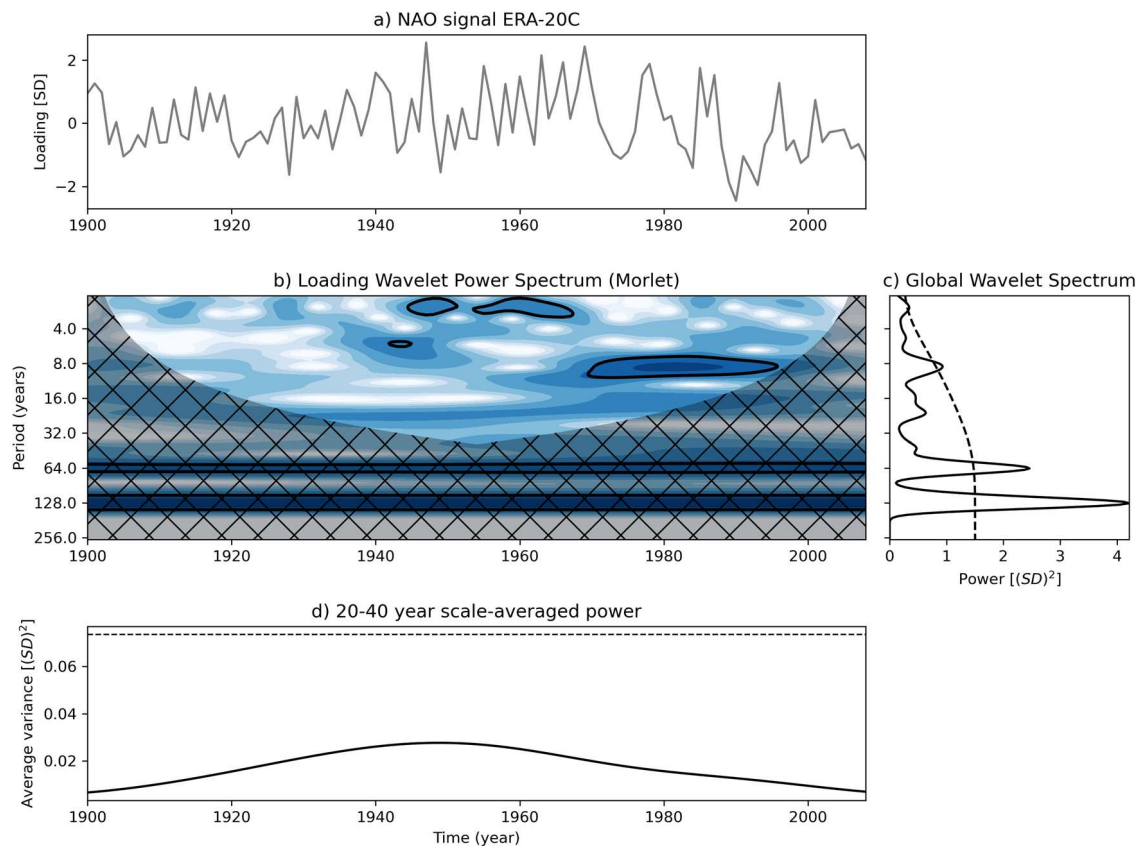


Fig. 3 Spectrum of the winter North Atlantic Oscillation (NAO) index 1900–2010. **a** Time series of the principal component of the first orthogonal function, **b** wavelet power, **c** power averaged over time and **d** wavelet power averaged for a period band of 20–40 years as a function of time. The black contour lines in the wavelet power spectrum show a 95% significance level⁶¹. The winter (December to February) NAO index was calculated from the reanalysis data ERA20C⁵⁸.

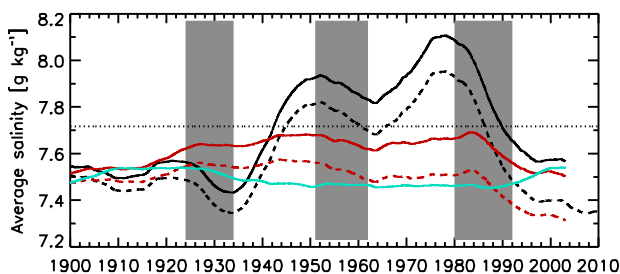


Fig. 4 Mean salinity of the Baltic Sea. Low-pass filtered, spatially averaged salinity with a cut-off period of 12 years in five numerical experiments: the reference simulation (REF+, black line), the reference simulation without a sea level rise (REF, black dashed line), and the sensitivity experiments with a climatological mean river discharge and constant net precipitation with (RUNOFF+, red line) and without (RUNOFF-, red dashed line) a sea level rise and with constant wind from 1904 (WIND, cyan line). As the salinity of the WIND simulation drifted during the simulation because the wind during 1904 was not representative of the mixing input during the entire period, a drift following an e-function with an e-folding time scale of 25 years was subtracted, and the curve was shifted by a constant offset to the start value of RUNOFF in 1900. Periods with a decreasing mean salinity and a preceding local maximum in the freshwater supply (1924–1934, 1951–1962, 1980–1992) are shown as grey-shaded areas. The periods in between (1935–1950 and 1963–1979) are characterised by an increasing mean salinity and a preceding local minimum in the freshwater supply.

Impact of the freshwater supply on saltwater inflows

As data on MBIs¹³ and river discharge show a significant wavelet coherence at the period of about 30 years, with river discharge preceding saltwater inflows by about 20 years (Supplementary Fig. 6), we examined whether the freshwater supply to the Baltic Sea has a causal influence on MBIs and found that the intensity of MBIs is modulated by the accumulated freshwater supply (Fig. 5). During periods with anomalously high (low) freshwater content in the Baltic Sea, the salinity of the MBIs decreases (increases), as indicated by the difference in the inflow volume with a salinity $> 17 \text{ g kg}^{-1}$ (V_{17}) between REF+ and RUNOFF+. Although changes in V_{17} are $< 3 \text{ km}^3$, or about 20% (Fig. 5), the accumulated salt transport on a decadal time scale has a significant impact on the Baltic Sea's salt content. As in the reconstructed MBIs¹³ shown in Supplementary Fig. 5, a period of about 30 years is discernible (Fig. 5).

Our model results thus indicate a positive feedback mechanism amplifying the multidecadal oscillations in the mean salinity of the Baltic Sea. As described in the study by Mohrholz¹³, barotropic salt transports can be approximated by the product of the inflow volume and the vertically averaged salinity in the Baltic Sea entrance area (S_B) after the so-called Kattegat–Skagerrak salinity front, separating saline North Sea and brackish Baltic Sea outflow waters⁴¹, has reached the sills (Fig. 1). S_B depends on the surface layer salinity, which at a multidecadal time scale is a function of the mean salinity of the Baltic Sea. As volume transports during saltwater inflows only show small differences in their intensities

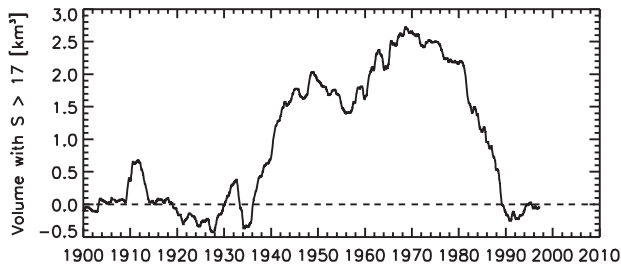


Fig. 5 Changes in saltwater inflow volume caused by low-frequency freshwater inputs. The differences in the low-pass filtered inflowing volume, with salinity $> 17 \text{ g kg}^{-1}$ and a cut-off period of 12 years, between the sensitivity experiments REF+ and RUNOFF+ are shown. The dashed line indicates zero.

with a negligible effect on mean salinity (see next sub-section), the multidecadal variations in MBLs can be explained by S_B alone. During periods characterised by an anomalously high freshwater content in the Baltic Sea, the S_B in the MBLs is, on average, smaller than during periods with an anomalously low freshwater content. Hence, the net salt import is reduced. As proof of this relationship, we calculated the surface and bottom salinity differences between REF+ and RUNOFF+ averaged during periods of decreasing mean salinity preceded by a local maximum in the freshwater supply for the years 1924–1934, 1951–1962, and 1980–1992 (Fig. 4). During these periods, the SSS in the Kattegat and the inflowing bottom salinity in the entrance area (Belt Sea) and Arkona Basin (for the location, see Fig. 1) were smaller in REF+ than in RUNOFF+ (Fig. 6a, b). Conversely, during periods with increasing mean salinity with a preceding, local minimum in freshwater supply, i.e., in 1935–1950 and 1963–1979, the SSS in the Kattegat and the inflowing bottom salinity in the entrance area (Belt Sea) and Arkona Basin were higher in REF+ than in RUNOFF+ (Fig. 6c, d). The results for V_{17} confirmed that saltwater transports related to MBLs increase (decrease) during periods of increasing (decreasing) mean salinity (Fig. 5).

Impact of wind anomalies on salinity

The results of our sensitivity experiment (WIND) suggested that the effects of the low-frequency variations of the wind on the mean salinity of the Baltic Sea (Fig. 4, blue curve) and the saltwater inflow volume V_{17} (not shown) are small. In the WIND, in addition to the constant freshwater supply, the wind fields of the year 1904 were repeated annually.

The period 1983–1992, during which there was no MBL, was an exception to the overall conclusion that wind plays only a minor role in the multidecadal salinity fluctuations¹³. During this so-called stagnation period, both the anomalously large freshwater surplus and the absence of wind patterns causing saltwater inflows resulted in a decline in the mean salinity (Fig. 4). Such stagnation periods are not unusual²¹. An analysis of paleoclimate simulations showed that periods of decreasing salinity over 10 years occur approximately once per century as part of the natural variability.

The winter mean SSS and the bottom salinity differences in RUNOFF+ between 1986–1997 and 1957–1982 are shown in Fig. 6e, f. These two periods were characterised by predominantly positive (1986–1997) and negative (1957–1982) NAO indices (Fig. 2). The SSS in the Kattegat and entrance area (Belt Sea) during 1986–1997 was higher than during 1957–1982 because of the higher sea level in the Kattegat. As a west wind hampers the outflow of surface layer water and consequently the saltwater inflow in the bottom layer at any north–south section within the Baltic Sea, the bottom salinity in the central Baltic Sea (Gotland Basin) was lower during 1986–1997 than during 1957–1982. An important role in the bottom salinity in the Gotland Basin is played

by the Słupsk Channel, which connects the western (Bornholm Basin) and central Baltic Sea. In the sensitivity experiment WIND, the bottom salinity difference in the central Baltic Sea between 1986–1997 and 1957–1982 was positive because of the absence of the hampering effect of the west wind (not shown).

Impact of the sea level in the Kattegat on salinity

The sea level in the Kattegat at the open boundary of the model domain correlated well with the daily variations of the meridional sea level pressure difference over the North Sea^{42,43}, which may suggest an effect on saltwater inflow at multidecadal time scales. However, the results of the sensitivity experiment WIND, with constant external forcing except for the varying sea level at the open boundary in the Kattegat, indicated only a small impact of low-frequency variations in the sea level of the Kattegat on the mean salinity.

DISCUSSION

Our model simulations for the past >100 years suggest that multidecadal variations in the freshwater supply roughly explain 52% of the multidecadal variations in the mean salinity of the Baltic Sea, in agreement with previous studies^{9,11}. According to Radtke et al.'s analytical approach¹¹, only about 27% of the variations can be explained by a 'direct dilution' effect. Hence, we conclude that most of the remainder of the 52% can be accounted for by a positive feedback mechanism operating between the accumulated freshwater supply and saltwater inflows into the Baltic Sea. During periods of enhanced freshwater supply, (1) the salinity in the surface layer decreases, (2) the location of the Kattegat–Skagerrak front moves northward, and (3) the salinity at the sills decreases. Consequently, inflow events are less saline and thereby amplify the freshening of the water body during phases of enhanced freshwater supply. As the turnover period of the freshwater content, i.e., the time scale of the internal response to external freshwater variations, roughly matches the period of external forcing in the multidecadal power band⁴⁴, this coincidence results in a considerable amplification of the salinity oscillations with a periodicity of about 30 years.

Based on Fig. 6, we estimate a peak-to-peak salinity difference—both at the sea surface and bottom and due to the moving Kattegat–Skagerrak front—of about 0.5 g kg^{-1} between selected decades with anomalous high and low freshwater input. This salinity difference would be roughly 2.5% of the salinity of 20 g kg^{-1} in the Baltic Sea entrance area. As the mean salinity varies by $\sim 7\text{--}8\%$ peak-to-peak (Fig. 4), at least about one-third of these variations can be roughly explained by the self-amplification effect, over and above the direct dilution effect¹¹. Hence, these two processes, dilution and amplification, explain most of the signal.

Due to the self-amplification mechanism and the unique setting of the Baltic Sea, systematic changes in its water balance, e.g., those resulting from an intensified hydrological cycle of Northern Europe or the changes in large-scale atmospheric circulation patterns caused by global warming⁴⁵, might be detected earlier in the Baltic Sea than elsewhere in the Northern Hemisphere.

Our sensitivity experiments allowed us to distinguish between the influences of the low-frequency oscillations in the freshwater supply, wind forcing, and the water level in the Kattegat on the salinity of the Baltic Sea. The results suggest a dominant effect of freshwater variations via direct dilution and the above-described feedback mechanism. The remaining low-frequency variability can be explained by the timing of saltwater inflows and, in particular, the absence of these events during stagnation periods. The direct impact of the multidecadal wind variability on transport in the sea redistributes the salinity within the Baltic Sea via Ekman dynamics⁴⁶, but the impact on the mean salinity variations is only minor.

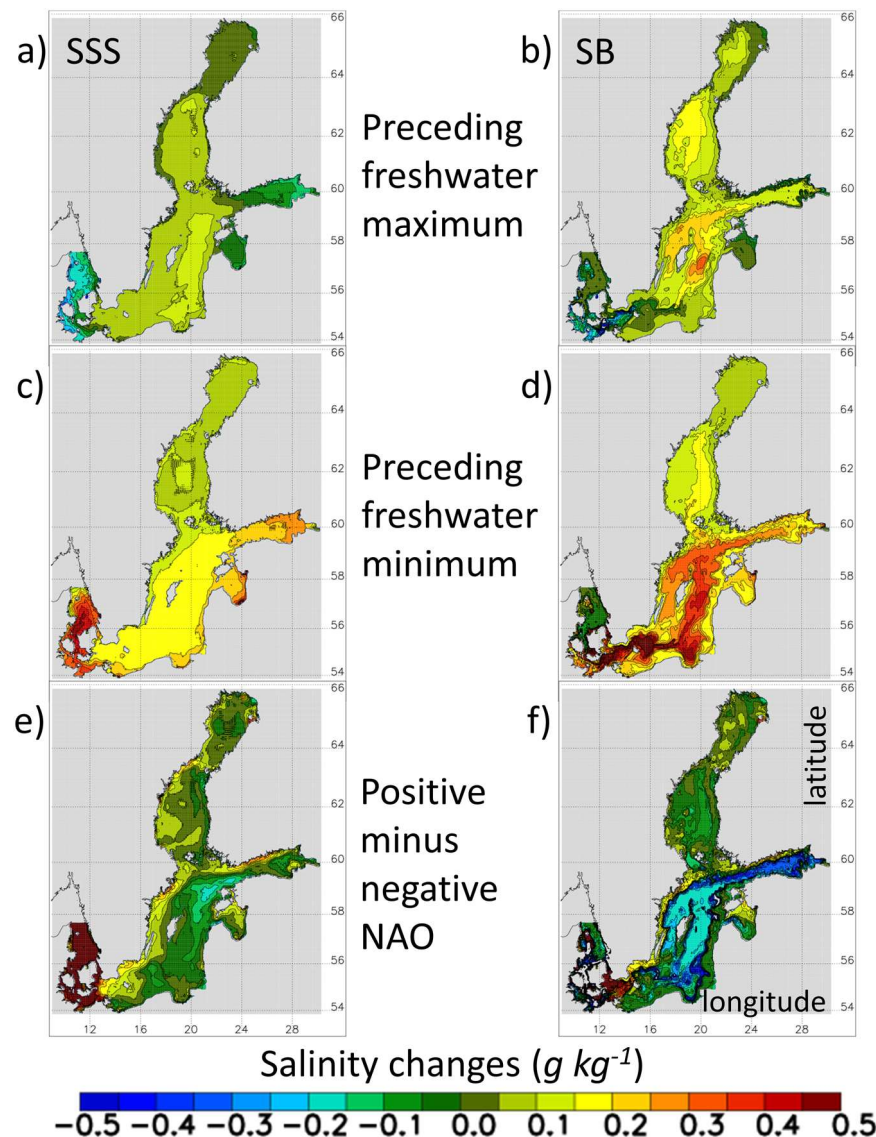


Fig. 6 Differences in sea surface and bottom salinities (in g kg^{-1}) caused by river discharge and west wind anomalies. a, b Differences in the autumn and winter mean (September to February), sea surface salinity (SSS) (a), and bottom salinity (SB) (b) between REF+ and RUNOFF+ averaged during 1924–1934, 1951–1962 and 1980–1992, i.e., periods with a decreasing mean salinity (Fig. 4) and with a preceding, local maximum in the freshwater supply (Fig. 2). **c, d** Same as (a) and (b) but showing the averaged salinity difference during 1935–1950 and 1963–1979 with increasing mean salinity (Fig. 4) and a preceding local minimum in the freshwater supply (Fig. 2). **e, f** Differences in the winter SSS (e) and bottom salinity (f) according to RUNOFF+ between 1986–1997 (a period with predominantly positive NAO indices, i.e., wet and with a low salinity) and 1957–1982 (a period with predominantly negative NAO indices, i.e., dry and with a high salinity).

The in situ observations of the national monitoring programme in the Baltic Sea for the period 1982–2016 showed a decrease in upper layer salinity of -0.005 , to $-0.014 \text{ g kg}^{-1} \text{ year}^{-1}$, and an increase in the sub-halocline deep layer salinity of $+0.02$ to $+0.04 \text{ g kg}^{-1} \text{ year}^{-1}$, thereby strengthening the stratification⁴⁷. Vertical stratification is controlled by saltwater inflows and vertical diffusion across the halocline. Hence, saltwater intrusions into the central Baltic Sea result in a sawtooth-like temporal progression of the unfiltered stratification record (not shown). In the absence of large saltwater inflows and the presence of an anomalously high freshwater supply, stratification decreased during the stagnation period 1980–1992. In 1993, it dramatically increased again. Hence, the temporal sequence of saltwater inflows, rather than the freshwater supply, mainly explains the trends since 1980 observed by Liblik and Lips⁴⁷. Although the freshwater supply largely controls multidecadal variations in mean salinity (Supplementary Fig. 3), which is mainly controlled by the SSS, the effect of

multidecadal freshwater input variations on the changes in stratification is smaller than the effect of MBIs over time scales >4 years (Supplementary Fig. 7). An accumulation of power within the 20- to the 40-year period band was not statistically significant (Supplementary Fig. 8).

METHODS

A detailed description of the Baltic Sea model setup was presented in a previous study¹⁰. Here we provide a summary of the physical module.

Model description

The Rossby Centre Ocean model, a three-dimensional ocean circulation model coupled to a Hibler-type, multi-category sea-ice model, was used^{48–51}. Subgrid-scale mixing in the ocean was

parameterised using a state-of-the-art k - ϵ turbulence closure scheme with flux boundary conditions. A flux-corrected, monotonicity-preserving transport scheme, without explicit horizontal diffusion, was embedded in the model. The model domain comprised the Baltic Sea and the Kattegat, with lateral open boundaries in the northern Kattegat (Fig. 1). The horizontal resolution was 3.7 km, and the vertical resolution was 3 m.

Atmospheric forcing

Regionalised reanalysis data for 1958–2007, historical station data of daily sea level pressure, and monthly air temperature observations were used in the reconstruction of multivariate 3-h, high-resolution atmospheric forcing fields (HiResAFF) for the period 1850–2008, based on the analogue method⁵². The latter searches for the atmospheric surface fields that are most similar to the historical observations in a library of predictands from the calibration period 1958–2007. The predictands or analogues are multivariate atmospheric forcing fields of 2 m air temperature, 2 m specific humidity, 10 m wind, precipitation, total cloud cover, and mean sea level pressure recorded in the Rossby Centre Atmosphere Ocean model⁵³, with a horizontal resolution of $0.25^\circ \times 0.25^\circ$ (~25 km) interpolated onto a regular geographical grid.

River discharge

Monthly mean river flows were calculated from several merged data sets (Supplementary Fig. 1). Since the inter-annual variability of the reconstructed river discharge was significantly underestimated before but not after 1900 (Supplementary Fig. 1), the analysis was limited to the period 1900–2008.

Lateral boundary data

Daily mean sea level elevations at the lateral boundary were calculated from the reconstructed meridional sea level pressure gradient across the North Sea⁴². Gustafsson et al.⁴³ calculated the correlations of the various frequency bands using empirical orthogonal functions (EOFs) to avoid underestimating extremes. The mean value of the time series was subtracted and replaced at the lateral boundary by the mean sea level in the Nordic Height System 1960⁵⁴. A linearly rising mean sea level of 1 mm year^{-1} relative to the sea bottom at the sills in the entrance area was implemented by continuously deepening the water depth at all grid points^{40,55}. A spatially differing land uplift with greater rates in the north than in the south was not considered. In the case of inflow, temperature and salinity were nudged towards the observed climatological seasonal mean profiles for 1980–2005 located north of the lateral boundary in Kattegat.

Initial conditions

After a spin-up simulation for 1850–1902 utilising the reconstructed forcing described above, the physical variables calculated for the end of the spin-up simulation on January 1, 1903, were used as the initial conditions for January 1, 1850.

Experimental strategy

A 159-year reference simulation for 1850–2008 was performed using the forcing data described above (henceforth referred to as REF+). In addition to REF+, four sensitivity experiments were carried out with the same experimental setup as in REF+ but with modified forcing data to identify the main drivers of the multidecadal variability (Table 1). The sensitivity experiments REF, RUNOFF and WIND have previously been analysed^{8,10}. In REF+ and RUNOFF+, the global eustatic sea level rise was considered.

The RUNOFF+ and RUNOFF sensitivity experiments with climatological mean freshwater input were conducted to investigate the effects of interannual to multiannual variations in river

discharge on the salinity of the Baltic Sea. In the WIND experiment, in addition to the freshwater input, interannual variations in atmospheric forcing were also neglected by repeating the 1904 atmospheric forcing for all years. The results of this sensitivity experiment show the effect of the low-frequency variations of the wind field on salinity. As 1904 does not contain an MBI event, the salinity decreases with an e-folding time scale of 25 years. Conversely, the atmospheric forcing with a year with MBI would result in a drift to higher salinity. However, regardless of the chosen sensitivity experiment, the influence of the multidecadal variations in the wind field on the salinity can be studied after subtracting the drift.

Previous studies concluded that ice cover in the Baltic Sea in the 20th century had no influence on salinity⁹. Therefore, this effect was not analysed here.

Evaluation of saltwater inflows

Sporadic events of large saltwater inflows, so-called MBIs, are essential for the ventilation of the Baltic Sea's deep water¹³. Simulated MBIs, calculated from the inflowing volume with salinity $> 17 \text{ g kg}^{-1}$ (V_{17}), were close to the MBIs calculated from the observations of Mohrholz¹³. The largest inflow on record was in 1951. Three out of the four largest MBIs, i.e. those in 1921, 1951, and 2014, were also identified as record events in the simulation when the reference run was prolonged⁵⁶. Only the MBI in 1898 was not reproduced, probably due to the inaccurate data used as forcing in our simulation or in the reconstruction of the MBIs¹³. Furthermore, a distinct stagnation period from 1983 to 1992 was identified in our simulation, as was also observed. This analysis demonstrated that our modelled MBIs sufficiently well reproduced the observed MBIs.

Evaluation of salinity at selected stations

Supplementary Fig. 2 shows the simulated and observed sea surface and bottom salinities at selected monitoring stations with relatively long records of observations (Fig. 1). At stations located within the Baltic Sea, the model accurately reproduced the pronounced multidecadal variability of about 30 years, both at the sea surface and the sea bottom (Supplementary Fig. 2, see also Fig. 4 and Supplementary Fig. 3). However, there was less agreement between the model's results and observations at the three available stations located in the entrance area, i.e., the Kattegat and the Great Belt. This was in part due to the sparse measurements in this area and to the difficulty of adequately evaluating the model in this highly dynamic transition area between the North Sea and the Baltic Sea. Furthermore, at some stations located in the central Baltic Sea (e.g., BY15, OMTF0286, BY31), there was also less agreement between the model's results for bottom salinity and observations during about 1950–1970. Probably the simulated intensity of the large MBI in 1951 is underestimated. Please note that long-term reconstructed atmospheric fields have been used as forcing data whose quality is less good than that of reanalysis data or observations. If high-quality atmospheric forcing data are used, the RCO model can reproduce saltwater inflows well⁵⁷.

For further results of the model evaluation, the reader is referred to Meier et al.¹⁰.

Observational datasets

The winter (December to February) NAO index was derived from long-term observations of the difference in sea level pressure between Reykjavik, Iceland, and Gibraltar, Spain (available from the Climatic Research Unit, University of East Anglia; <https://crudata.uea.ac.uk/cru/data/nao/nao.dat>)³⁷ and from an EOF analysis of the reanalysis data ERA20C⁵⁸. Despite differences in the resulting records, the conclusions of this study do not depend on

the method used to calculate the NAO index. The annual mean AMV index was calculated from SST anomalies recorded in the HadISST dataset⁵⁹ averaged over the North Atlantic between 0 and 70°N latitude. Precipitation data from the HiResAFF dataset⁵² were averaged over the Baltic Sea catchment area between 9.6°E and 32°E and between 52.4°N and 67.4°N. The simulated salinity was evaluated using observations from the International Council for the Exploration of the Sea (ICES) at <https://www.ices.dk/data/data-portals/Pages/ocean.aspx>. These measurements were post-processed to fill gaps, following the method of Radtke et al.¹¹.

DATA AVAILABILITY

The observational and model data analysed in this study and displayed in the figures are publicly available from the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) at the doi server <https://doi.io-warnemuende.de/10.12754/data-2023-0001>. Water depth data compiled by Seifert and Kayser⁶⁰ and saltwater inflow data D55 calculated by Mohrholz¹³ are publicly available from <https://www.io-warnemuende.de/topography-of-the-baltic-sea.html> and <https://www.io-warnemuende.de/major-baltic-inflow-statistics-7274.html> (<http://doi.io-warnemuende.de/10.12754/data-2018-0004>), respectively. These datasets are provided through the Creative Commons (CC) data license of type CC BY 4.0 (<https://creativecommons.org/licenses/by/4.0/>).

CODE AVAILABILITY

The model code of the ocean model used for the historical simulations is publicly available from the Swedish Meteorological and Hydrological Institute, Norrköping, Sweden (<https://www.smhi.se>, E-mail: smhi@smhi.se).

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AUTHOR CONTRIBUTIONS

H.E.M.M. designed the research, performed the sensitivity simulations, analysed the model results and wrote the paper with the help of all co-authors: L.B., F.B., M.G., L.N. and H.R. L.B. and F.B. performed the wavelet analyses and L.N. analysed the model results vs. observations. H.R. prepared the salinity observations and analysis tools.

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The authors declare no competing interests.

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