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Changes in Seasonality of Saltwater Inflows Caused Exceptional Warming Trends in the Western Baltic Sea

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Key Points:

- Summer and early autumn salt import into the Baltic Sea increased significantly since 1851 compared to the annual salt import
- Salt import between June and October is highly correlated with the annual sub-thermocline temperature maximum in the western Baltic Sea
- The shift in inflow seasonality was partly caused by seasonal changes in river runoff

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract During the last decades, the Baltic Sea has been among the fastest warming seas in the world. The warming is mainly driven by increasing air temperatures but deeper water layers can also be warmed by lateral advection of heat. By analyzing a 159 years long (1850–2008) hindcast simulation of the Baltic Sea, we link the exceptionally strong bottom water warming in the western Baltic Sea to a shift in the seasonality of saltwater inflows from the North Sea to the Baltic Sea. Over the model period, warm summer and early autumn inflows have increased while cold winter inflows have decreased. Sensitivity experiments reveal that these changes were partly driven by a shift in river runoff seasonality. The strong warming could lead to faster oxygen depletion in the affected layers and thus have ecological consequences.

Plain Language Summary The Baltic Sea is home to various marine and freshwater species and an important economic factor for the surrounding countries. Like other seas, the Baltic Sea is getting warmer due to climate change. The water at the surface warms especially fast because it takes up heat from the warming atmosphere. After some time, temperatures also increase in deeper layers. However, some deep parts in the western Baltic Sea are warming even faster than the sea surface. In our study, we investigate if the exceptional warming can be explained by an increase in warm saltwater inflows from the North Sea. Hence, we use a model simulation of the Baltic Sea for over 150 years to compare long time series of warm inflows and the temperatures in the deep layers of the western Baltic Sea. We find a strong correlation. Thus, we can link the exceptional warming in the deep layers of the western Baltic Sea during the last decades to an increase in warm inflows. The warming has ecological consequences since in warmer water, the oxygen is consumed faster and the deep water layers of the Baltic Sea are suffering from low oxygen concentrations.

1. Introduction

According to the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), the global mean sea surface temperature has increased by about 0.9°C since 1900 (IPCC, 2021). One of the fastest warming seas is the shallow, semi-enclosed Baltic Sea (Belkin, 2009) with an increase in sea surface temperature of about 0.3–0.6°C per decade since 1980 (Liblik & Lips, 2019; Meier et al., 2022). The surface warming is mainly driven by increasing air temperatures (Dutheil et al., 2022a; Kniebusch, Meier, Neumann, & Börgel, 2019). Since the Baltic Sea is strongly stratified, vertical exchange between the well-mixed surface layer and deep water below the permanent halocline in 50–80 m depth (Väli et al., 2013) is rather limited. Thus, lateral advection of heat plays a major role for the warming of the deep basins in the western and central Baltic Sea (Meier et al., 2022).

An exceptionally strong bottom water warming compared to other basins of the Baltic Sea was detected in the Bornholm Basin (western Baltic Sea, Figure 1) (Dutheil et al., 2022b; Mohrholz et al., 2006). Mohrholz et al. (2006) linked it to increased summer and early autumn saltwater inflows (in the following labeled "summer inflows") which transport warm surface water from the Baltic Sea entrance area to deep layers of the western and central Baltic Sea.

In general, the inflow of saline North Sea water into the Baltic Sea is hampered by shallow sills in the Danish straits, namely the Darss Sill (19 m) and the Drogden Sill (8 m, see Figure 1) (Mohrholz, 2018b). Very large so-called Major Baltic Inflows (MBIs) can only happen if, first, easterly winds push water out of the Baltic Sea for about 3 weeks and, second, westerly winds of a comparable duration push large amounts of saline water back over the sills (Lass & Matthäus, 1996). Such wind patterns occur roughly once per year between autumn and early spring (Matthäus & Franck, 1992; Mohrholz, 2018b). In contrast to that, small- to medium-sized inflows happen throughout the year (Mohrholz, 2018b). Unlike MBIs, they cannot reach the deepest parts of the central Baltic Sea and supply them with fresh oxygen but they mainly interleave in or below the halocline (Elken, 1996;

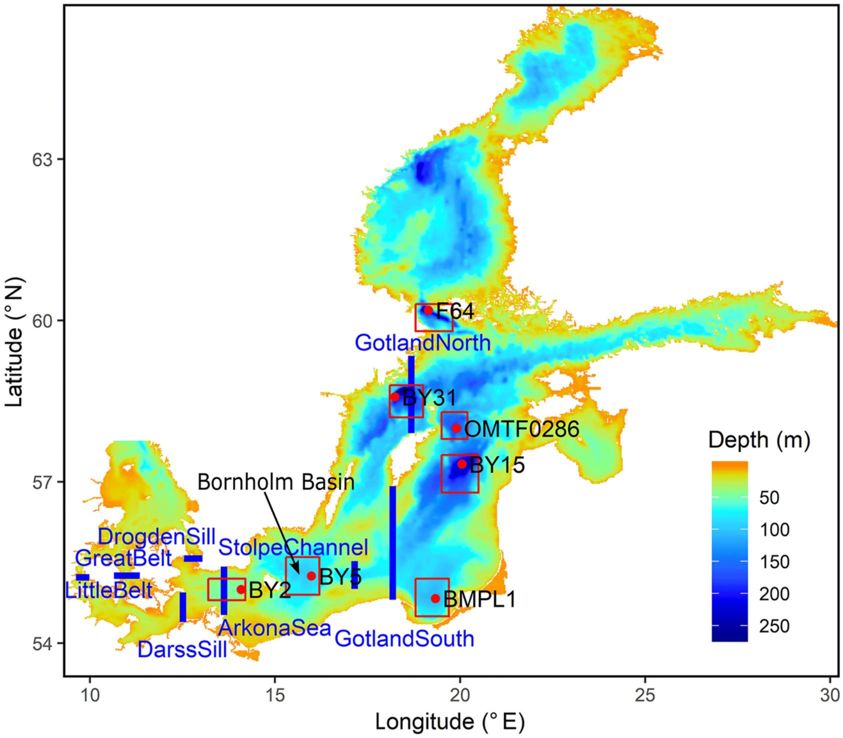

Figure 1. Model topography. Blue lines indicate transects across which salinity-discriminated salt transport is computed. The Bornholm Basin (western Baltic Sea) is marked. Red stations are used for model validation. Red squares show areas from which ICES data for the respective stations are taken. Modified from Radtke et al. (2020).

Matthäus & Franck, 1992; Mohrholz et al., 2006). Small- and medium-sized inflows can be both barotropic (driven by sea level gradients, mainly due to wind) or baroclinic (driven by horizontal salinity gradients during periods of calm weather) (Feistel et al., 2006; Wolf, 1972). Summer inflows are believed to be mainly baroclinic (Feistel et al., 2006).

The first pronounced summer inflow that was intensively investigated occurred in 2002 (Feistel et al., 2003, 2006; Mohrholz et al., 2006). Consequently, there is no long time series of summer inflows derived from observations like the ones that exist for MBIs (Fischer & Matthäus, 1996; Mohrholz, 2018b). However, such a time series would be necessary to detect systematic trends in summer inflows and distinguish it from the multidecadal variability which characterizes the water cycle in the Baltic Sea (Kniebusch, Meier, & Radtke, 2019; Lehmann et al., 2022; Meier & Kauker, 2003a; Mohrholz, 2018b; Radtke et al., 2020; Schimanke & Meier, 2016).

In this study, we investigate systematic changes in the seasonality of saltwater inflows during the last decades and whether those changes contributed to the exceptional temperature trend in the Bornholm Basin. In order to get a continuous and long time series of salt import from small, medium and large inflows, we analyze a long (1850–2008) hindcast simulation of the Baltic Sea. Furthermore, we conduct several sensitivity experiments where we modify different drivers of salinity dynamics, namely river runoff, wind and sea level. With this, we aim to quantify the impact of these drivers on any possible long-term changes in inflow activity.

The strong warming of the Bornholm Basin might have severe consequences for the ecosystem. Like in other basins in the central Baltic Sea, the deep water of the Bornholm Basin is hypoxic or even anoxic most of the time (Almroth-Rosell et al., 2021; Krapf et al., 2022). Higher bottom temperatures speed up mineralization of organic matter in the sediments and cause increased oxygen consumption (Krapf et al., 2022; Laufkötter et al., 2017). Warm saline inflows can also lead to a (temporal) eastward spread of non-indigenous species' habitats (Hinrichsen et al., 2022). Our results provide a more comprehensive understanding of temperature variability in the deep Bornholm Basin and thus help to investigate its ecological consequences. Furthermore, the mechanisms of bottom warming might be applicable to other strongly stratified coastal seas like the Chesapeake Bay which also suffers from (seasonal) hypoxia that is exacerbated by global warming (Ni et al., 2019; Tian et al., 2022, e.g.,).

2. Materials and Methods

2.1. Data and Model Setup

The characteristics of the reference simulation are summarized in Radtke et al. (2020). They performed a simulation of the Baltic Sea (Figure 1) from 1850 to 2008 using the General Estuarine Transport Model (GETM) with 1 nautical mile horizontal resolution and 50 vertical layers with adaptive coordinates (Gräwe et al., 2019). The latter allow to increase the resolution in depths with strong density gradients which leads to a more realistic simulation of inflows (Hofmeister et al., 2011). For the time series of monthly river runoff, different data sets were merged (Meier et al., 2019). At the lateral boundary of the model domain, daily mean sea level elevations were obtained from a reconstruction of the meridional sea level pressure gradient across the North Sea (Meier et al., 2019). Atmospheric forcing was provided by the HiResAFF (High Resolution Atmospheric Forcing Fields) v2 data set which was prepared with the analogue method (Schenk & Zorita, 2012).

2.2. Model Validation

For model validation, mean vertical temperature and salinity profiles from 1970 to 2007 at selected stations are compared to observational data from the ICES oceanographic database (Figure S1 in Supporting Information S1) (ICES, 2023). The ICES data are processed as in Radtke et al. (2020). Modeled and observed profiles exhibit the same qualitative features, namely the seasonal thermocline and the permanent halocline, but the latter tends to be shallower in the model data. This could be due to underestimated mixing or too weak winds. Modeled salinities are generally too high. Most important for an accurate simulation of summer inflows is the reproduction of the salinities in/below the halocline in the western Baltic Sea (stations BY2 in the Arkona Basin and BY5 in the Bornholm Basin). Here, the modeled values lie within 1 standard deviation of the ICES data. Time series of bottom and surface salinities were already validated by Radtke et al. (2020). They found that the multidecadal variability in surface and bottom salinities is in general well represented by the model. In case of the annual mean bottom salinity, the explained variance is highest at the northernmost stations (BY31, OMTF0286, and F64) with more than 50% and lowest at BY5 (17.4%). However, the explained variance at BY5 in 60 m depth, at the relevant height for small and/or warm inflows, is much better with 34%. Radtke et al. (2020) additionally analyzed the transport across the Darss and Drogden sills. They found a correlation of 58.6% for the daily mean volume transport across Drogden Sill and correlations of 43.5% (3 m depth) and 40.5% (17 m depth) for the daily mean eastward velocity at Darss Sill between 1995 and 2008.

2.3. Inflow Classification

In order to detect saltwater inflows into the Baltic Sea, salinity-discriminated transports are computed from the model output for selected transects (see Figure 1) following the Total Exchange Flow framework (Burchard et al., 2018; MacCready, 2011; Walin, 1977) as in Radtke et al. (2020). Afterward, we choose the transects “DarssSill” and “DrogdenSill” for the actual inflow detection since the two sills are the main barriers for the inflowing water. Finally, we introduce salt import thresholds to separate individual inflows from each other and only count inflows from a certain size. Too small inflows might just mix with the ambient water in the Arkona Basin but not reach the other basins further downstream. We follow these steps:

1. From salinity-discriminated salt transport at Darss Sill and Drogden Sill transects, the total inward salt transport by water masses with a salinity larger than 17 g/kg is extracted. This empirical salinity threshold was first introduced by Wolf (1972) to distinguish inflowing saltwater from the ambient water in the Danish straits and is commonly used in the literature to detect MBIs (Matthäus & Franck, 1992; Meier & Kauker, 2003a; Mohrholz et al., 2015).
2. The total salt import per day is calculated.
3. Days with salt import <20 Mt are neglected.
4. Consecutive inflow days are summed up.
5. Inflows with at least 100 Mt salt import are registered.

To justify our inflow criteria, we compare our salt import time series with the DS1 series of barotropic inflows by Mohrholz (2018a) which, in contrast to earlier observation-based inflow reconstructions, is unaffected by inhomogeneities in the salinity observations at Darss Sill (Mohrholz, 2018b). Figure S2 (Supporting Information S1) shows that the low frequency variability is comparable. Since our time series consists of barotropic and baroclinic inflows, the total annual salt import is higher than in the DS1 series. The smallest inflows from the DS1 series are in the same order of magnitude as our salt import threshold of 100 Mt.

2.4. Sensitivity Experiments

In addition to the reference simulation (REF), the following sensitivity experiments are conducted in order to quantify the impact of drivers affecting the salinity dynamics:

1. RUNOFF: The interannual variability of river runoff is removed by computing the long-term monthly runoff climatology of the respective rivers and repeating it for each year of the modeled time period.
2. WIND: Meteodata and sea level at the open boundary are high-pass filtered with a cut-off period of 11 years. Linear trends are removed before high-pass filtering and afterward added again to the filtered time series.
3. RUNOFF2: We remove changes in runoff seasonality by applying a climatological seasonal cycle but keep the interannual runoff variability.
4. noSLR: We remove the linear trend in the sea level at the open boundary which reflects the global mean sea level rise (SLR).

High-pass filtering in WIND and detrending in noSLR are done for each grid cell separately. It should be noted that we only modify the runoff in RUNOFF and RUNOFF2, that is, the net precipitation (precipitation minus evaporation) over the catchment area of the Baltic Sea, but not the net precipitation over the Baltic Sea itself. Since the latter only contributes roughly 10% of the total freshwater supply (Meier & Kauker, 2003b), its variability is negligible compared to the runoff variability.

3. Results

In order to identify changes in inflow seasonality, we compare the salt import by inflows detected according to the steps described in Section 2.3 for three different periods: Summer (June– August; JJA), early autumn (September–October; SO) and the entire year. Figure 2a shows the three time series. They are smoothed by 11-year running means to extract the previously mentioned multidecadal variability. Linear trends from 1851 show that the normalized salt import in summer and early autumn increased more strongly than the annual salt import. Both trends are significant with p-values below 0.05 (Wald Test). More specifically, summer salt import was highest between 1960 and 1980 and early autumn salt import at the end of the 1990s. The interannual variability of runoff before 1900 is probably underestimated (Meier et al., 2019) and before 1920, the runoff data are not properly resolved for the different basins (not shown). Since this might have affected the salinity dynamics, we also compute trends from 1920. We find that the trend for SO is significantly positive while the one for JJA is slightly negative (Figure 2).

In Figure S3 (Supporting Information S1), we compare the average monthly salt import for three 30-year periods (1865–1895, 1920–1950, and 1975–2005) which are equally distributed over the model period. The strongest increase toward the last period happened in October while the salt import in winter decreased. For the later two periods, we also compare two-dimensional maps of bottom salinity in the western Baltic Sea. The most pronounced change in early autumn is found in the Baltic Sea entrance area where the bottom salinity increased strongly (Figure 3).

As described in Section 1, the exceptionally strong bottom water warming in the Bornholm Basin could have been (partly) caused by increased summer inflows and reduced winter inflows (Dutheil et al., 2022b; Kniebusch, Meier, Neumann, & Börgel, 2019). Figure 4 compares June– October (JJASO) salt import, that is, the whole "warm" inflow season, with the annual sub-thermocline vertical temperature maximum in the Bornholm Basin. Both smoothed time series exhibit a similar multidecadal variability. The time series of annual means are significantly correlated with Pearson correlation coefficients of 0.53 (from 1851) and 0.55 (from 1920). Thus, the previously mentioned attribution is reasonable.

We conducted the sensitivity experiments RUNOFF, RUNOFF2, WIND, and noSLR to find out which of the different drivers of salinity dynamics caused the shift in inflow seasonality. The resulting smoothed salt import time series are shown in Figure S4 in Supporting Information S1 and the respective differences to REF in Figure S5 (Supporting Information S1). For all runs, the multidecadal variability is very similar. The largest deviations exist between REF and RUNOFF, especially in summer (JJA) around 1970. RUNOFF2 is quite similar to RUNOFF in case of JJA salt import (visible in Figure S5 in Supporting Information S1). A comparison of the linear trends

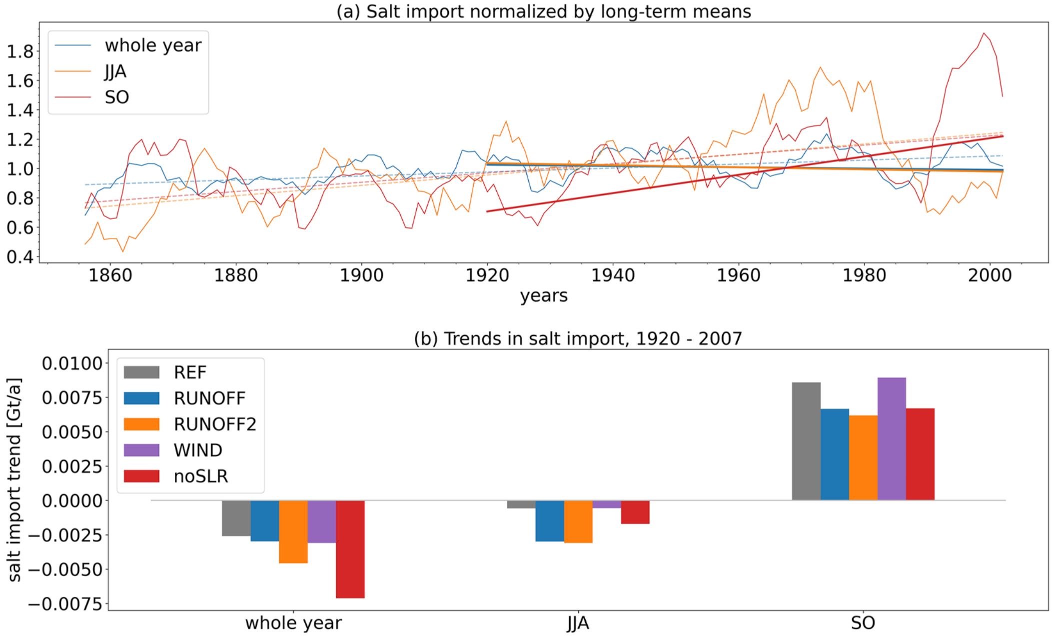

Figure 2. (a) 11-year running means of salt import per year, June– August (JJA) and September– October (SO) with linear trends from 1851 to 1920. All values were normalized by respective long-term means. (b) Trends in salt import from 1920 for the reference simulation REF and sensitivity experiments RUNOFF, RUNOFF2, WIND and noSLR.

in JJA and SO salt import since 1920 shows that the trends in RUNOFF and RUNOFF2 are less positive in SO and more negative in JJA compared to REF and WIND (Figure 2b), indicating that changes in the seasonality of river runoff were the most important driver of the shift in salt import seasonality. In the following section, we will examine a potential driving mechanism. However, as the shift in salt import seasonality is not completely absent in RUNOFF and RUNOFF2, we also need to discuss a possible impact of the other drivers (wind and sea level).

4. Discussion

We analyzed a long hindcast simulation of the Baltic Sea and found that salt import from summer inflows has increased during the model period and is strongly correlated with the annual sub-thermocline temperature

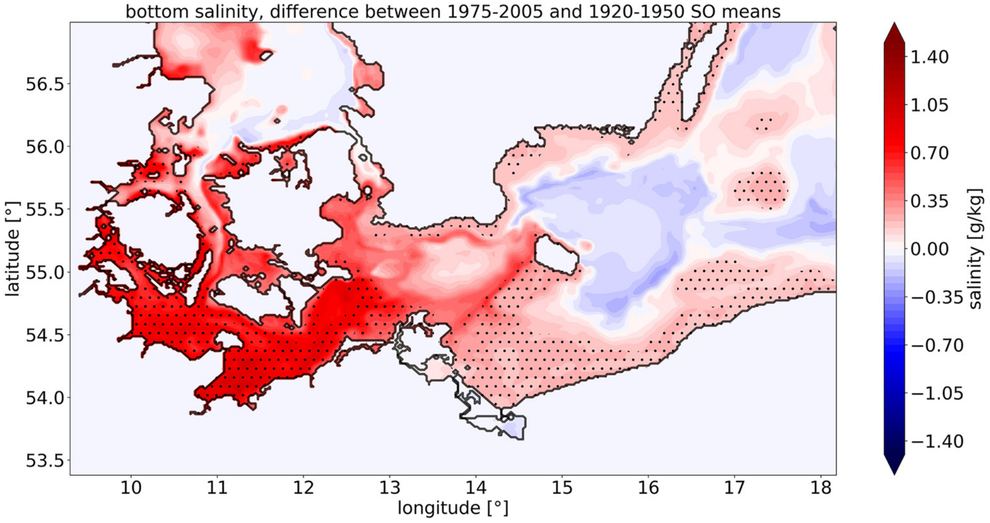

Figure 3. Differences between 1975–2005 and 1920–1950 September– October (SO) means of bottom salinity. Black dots indicate significant changes according to a Student's *t* test with a significance level of 0.95.

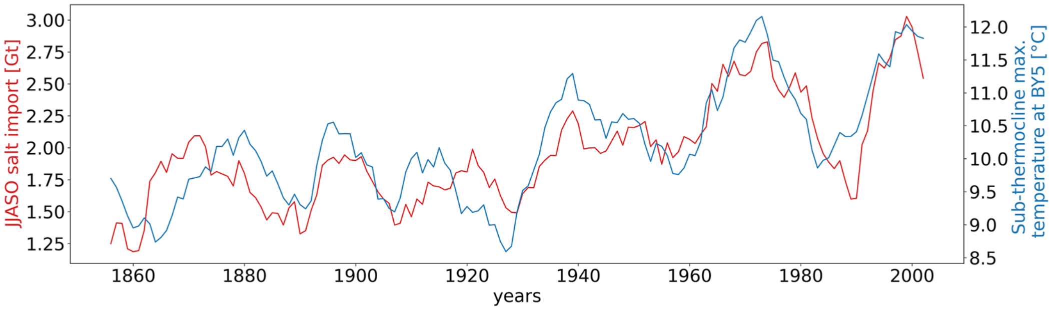

Figure 4. 11-year running means of June– October (JJASO) salt import versus annual temperature maximum below the seasonal thermocline (below 40 m) at station BY5 (Bornholm Basin, for the location see Figure 1).

maximum in the Bornholm Basin. Our sensitivity experiments switched off potential drivers of the observed changes. We found that the variability of the summer inflow time series is most strongly affected in RUNOFF and RUNOFF2, that is, if changes in seasonality of river runoff are ignored.

4.1. Runoff

Concerning accumulated runoff to the Baltic Sea, no significant trend could be found for the 20th century (Meier & Kauker, 2003a). However, there have been changes in seasonality. Meier and Kauker (2003a) have shown that winter and early spring runoff increased significantly since the 1970s, mainly due to river regulation in Sweden and Finland and increased precipitation in winter which is likely related to climate change (Meier et al., 2022). Already Wolf (1972) stated that the seasonality of river runoff affects the probability for highly saline inflows. However, it is not evident why seasonal changes in runoff should lead to seasonal changes in summer inflows since the response scale of Baltic Sea salinity to changes in external forcing is of the order of 30 years (Meier & Kauker, 2003a, 2003b; Winsor et al., 2001).

One mechanism could be a barotropic signal, that is, a change in sea level difference between Baltic Sea and North Sea due to runoff variability. This hypothesis was already raised by Schinke (1996) but he could not prove a causal connection between runoff and saltwater inflow seasonality via the sea level. The sea level in the Baltic Sea exhibits a seasonal cycle with a maximum in late summer or winter and a minimum in spring (Hünicke & Zorita, 2008; Meier et al., 2022; Stramska et al., 2013). According to Hünicke and Zorita (2008), the maximum shifted from late summer to winter during the 20th century, possibly due to changes in precipitation and runoff. Since, for inflows, the sea level gradient in the Baltic Sea entrance area is crucial, we compute the sea level difference between the stations AnholtE and BY2 (for the locations see Figure 1). By comparing 11-year running means of SO sea level difference and salt import, we find that the latter reaches its maximum when the former is minimal (Figure S6 in Supporting Information S1). Changes in sea level difference are only in the range of a few centimeters but in a barotropic inflow situation, even a 1 cm larger sea level difference can lead to a few megatons more salt import if we use Equation 3 in Mohrholz (2018b) for estimating the barotropic volume transport. No comparable correlation is found for JJA.

Finally, we conducted experiment RUNOFF2 with interannual runoff variability but without seasonal changes to get a more profound estimation of the effect of seasonality. As explained in the previous section, the trends in JJA and SO salt import since 1920 are quite close for RUNOFF and RUNOFF2 (Figure 2b). Thus, an impact of runoff seasonality seems possible although the signal is small.

4.2. Wind

Only part of the trend in summer salt import can be explained by the freshwater supply. Hence, wind changes could play a role, too. To present knowledge, there is no systematic overall trend in wind speed over the Baltic Sea (Meier et al., 2022). Coumou et al. (2015) reported a weakening of the atmospheric circulation in summer over mid-latitudes of the northern hemisphere. This could have caused more calm weather periods which are favorable for summer inflows. However, they considered the period 1979–2013 which is rather short and not comparable to our model period.

We analyze the third power of wind speed, which serves as a proxy for the energy input into the ocean by the wind, over the Baltic Sea from HiResAFF forcing between 1920–1950 and 1975–2005. It increased for SO means (Figure S7 in Supporting Information S1 left). Consequently, wind-driven inflows could have intensified. However, the changes are not significant except for a few grid cells. For summer (JJA), we observe decreasing third power of wind speed (Figure S7 in Supporting Information S1 right) between 1920–1950 and 1960–1990 which could have led to more summer inflows. But again, trends are not significant.

The positive trend in summer salt import in WIND is comparable to that in REF (Figure 2b). Still, one has to keep in mind that only the low-frequency variability of wind fields was filtered out in WIND while single inflow events result from variations in wind on a much shorter time scale. It cannot be ruled out that changes in large-scale atmospheric patterns like Scandinavian Blocking occurred and led to changes in high-frequency wind variability but a more profound analysis of atmospheric circulation patterns is beyond the scope of this study.

4.3. Sea Level Rise

Model studies indicate that a higher mean sea level in the North Sea and Baltic Sea will amplify the intensity of saltwater inflows in the future since it enlarges the cross section of the Danish straits (Meier et al., 2017, 2021; Saraiva et al., 2019). As the sea level in the Baltic Sea increased by roughly 20 cm since 1900 (Meier et al., 2022), that effect could have played a role during our model period. Indeed, our sensitivity experiment noSLR shows smaller/more negative trends in salt import compared to REF (Figure 2b). Hordoir et al. (2015) assumed that SLR leads to reduced mixing in the Danish straits and thus to stronger summer inflows. However, Arneborg (2016) questioned their approach and argued that rather the Sound will play a more important role for future saltwater inflows under a rising sea level. Our analysis does not show an impact of the global SLR on the seasonality of inflows since the smaller/more negative trends in noSLR are independent of the season.

4.4. Summary

To summarize the discussion, it is likely that the increase in early autumn (SO) salt import toward the end of the 20th century was mainly of barotropic nature (not baroclinic as commonly assumed), that is, driven by sea level alterations, which were likely caused by changes in runoff seasonality and wind. Concerning the summer (JJA) salt import maximum between 1960 and 1980, the drivers are less clear. Runoff variability and seasonality but also weaker winds could have played a role. Since maxima in JJA and SO salt import do not coincide in time and are perhaps not caused by the same drivers, we cannot exclude the possibility that the trends in JJA and SO salt import are part of multidecadal variations. As mentioned earlier, the main period of multidecadal variability in the Baltic Sea is about 30 years which is shorter than the time scale of the observed changes. However, we know that the Atlantic Multidecadal Variability influences the Baltic Sea water cycle on time scales longer than 60 years (Börgel et al., 2018). A longer modeling period would be necessary to detect more reliable trends.

5. Conclusions

For the first time, we showed a direct link between the exceptional bottom water warming in the Bornholm Basin (western Baltic Sea) and a shift in seasonality of saltwater inflows into the Baltic Sea. While summer and early autumn salt import has increased over the model period, winter salt import decreased. With the help of sensitivity experiments, we were able to attribute part of the changes to a shift in runoff seasonality due to river regulations and climate change. Another driver might be variations of the large-scale atmospheric circulation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The modeled and observational data necessary to reproduce the figures of this paper and its Supporting Information S1 are publicly available under https://doi.io-warnemuende.de/10.12754/data-2023-0006. The DS1 inflow series prepared by Volker Mohrholz can be downloaded from https://doi.io-warnemuende.de/10.12754/data-

2018-0004 (Mohrholz, 2018a). These datasets and Figure 1 from Radtke et al. (2020) are provided through the Creative Commons (CC) data license of type CC BY 4.0 (https://creativecommons.org/licenses/by/4.0/). The GETM model used for this study is open-source software and available under https://getm.eu/ (IOW, 2023).

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