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Variations of temperature, salinity and oxygen of the Baltic Sea for the period 1950 to 2020

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Abstract Variations of temperature, salinity and oxygen of the Baltic Sea on interannual to decadal timescales were studied for the period from 1950 to 2020. Both observational data and the output of a numerical circulation model of the Baltic Sea were analyzed. In addition, we investigated the influence of atmospheric parameters and river runoff on the observed hydrographic variations. Variability of sea surface temperature (SST) closely follows that of air temperature in the Baltic on all timescales examined. Interannual variations of SST are significantly correlated with the North Atlantic Oscillation in most parts of the sea in winter. The entire water column of the Baltic Sea has warmed over the period 1950 to 2020. The trend is strongest in the surface layer, which has warmed by 0.3–0.4°C decade^{-1}, noticeably stronger since the mid-1980s. In the remaining water column, characterized by permanent salinity stratification in the Baltic Sea, warming trends are slightly weaker. A decadal variability is striking in surface salinity, which is highly correlated with river runoff into the Baltic Sea. Long-term trends over the period 1950–2020 show a noticeable freshening of the upper layer in the whole Baltic Sea and a significant salinity increase below the halocline in some regions. A decadal variability was also identified in the deep layer of the Baltic Sea. This can be associated with variations in saltwater import from the North Sea, which in turn are influenced by river runoff: fewer strong saltwater inflows were observed in periods of enhanced river runoff. Furthermore, our results suggest that changes in wind speed have an impact on water exchange with the North Sea. Interannual variations of surface oxygen are strongly anti-correlated with those

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of SST. Likewise, the positive SST trends are accompanied by a decrease in surface oxygen. In greater depths of the Baltic Sea, oxygen decrease is stronger, which is partly related to the observed increase of the vertical salinity gradient.

1. Introduction

Due to the brackish water conditions, the ecosystem in the Baltic Sea is unique and vulnerable. Most species already live at the edge of their comfort zone and small changes in the water properties could cause shifts in the ecosystem. Therefore, the question of how a changing climate affects the Baltic Sea is of particular interest. To investigate what changes and variations of hydrography can already be observed in the Baltic Sea is part of this work. The focus is mainly on the variations of temperature, salinity and oxygen as these are not only characteristic parameters for identifying and comparing different types of watermasses but also significantly determine the living conditions in marine ecosystems.

The Baltic Sea is a semi-enclosed basin in northeast Europe and one of the largest brackish seas on Earth (Figure 1). On the long-term mean, salinity is consistent with the water balance in the Baltic Sea (Omstedt and Rutgersson, 2000). The main components of the freshwater budget are river runoff, net precipitation (precipitation minus evaporation) and water exchange with the North Sea at the entrance area. Because of the dominant river runoff, the water budget is strongly positive and a general outflow of brackish Baltic Sea water into the Kattegat results from the freshwater surplus. This is compensated by an inflow of higher saline bottom water from the Skagerrak and Kattegat into the Baltic Sea (for details see Leppäranta and Myrberg, 2009). The basin-like topography with shallow sills restricts the horizontal spread of dense bottom water in the Baltic Sea. Irregular barotropic exchange flows such as Major Baltic Inflows (MBIs, Matthäus and Schinke, 1999) and Large Volume Changes (LVC, Lehmann et al., 2017) are needed to renew the bottom waters in the Baltic deeps. Those inflows take place sporadically and can be observed as high salinity and oxygen peaks in time series of the deep waters all the way from the western Baltic to the northern Baltic Proper (Liblik et al., 2018; Mohrholz, 2018). There is no long-term trend in MBI occurrence (Mohrholz, 2018) and the frequency of large volume changes (Lehmann and Post, 2015). Salinity changes in the Baltic Sea are rather dominated by multidecadal variability with a period of about 30 years, likely driven by changes in river runoff and wind (Kniebusch et al., 2019b; Meier and Kauker, 2003).

Water temperature in the Baltic Sea, especially in winter, follows the two-layer structure determined by the salinity distribution. In the upper layer, the temperature is mainly driven by solar radiation and air-sea interactions. During summer, an additional surface layer forms, separating the upper layer into a mixed layer and a cold intermediate layer below. The permanent halocline, usually located at a depth of 40–80 m (Leppäranta and Myrberg, 2009), prevents vertical exchange and decouples the higher saline layer from the brackish surface layer. Temperature variations in and below the halocline are mainly caused by advection from salt water inflows in this layer. Long-term trends of sea surface temperature show much greater warming in the Baltic Sea than the global mean, with the strongest trends since the mid-1980s (Kniebusch et al., 2019a; MacKenzie and Schiedek, 2007). In recent decades, SST trends of about 0.4–0.6°C per decade have been observed in the Baltic Sea (BACC II Author Team, 2015; Lehmann et al., 2011; Liblik and Lips, 2019; Tronin, 2017).

Oxygen content in the Baltic Sea is determined by uptake from the atmosphere, vertical and lateral transport, and consumption of oxygen by biogeochemical processes (Lehmann et al., 2022). As a result of the limited vertical convection through the halocline, deep water masses are often poorly oxygenated and anoxic conditions can be found at the bottom. A strong increase of hypoxia in the Baltic Sea during the last century due to increased nutrient inputs and higher water temperatures was reported by Carstensen et al. (2014). During an MBI, oxygen-rich water is brought into the Baltic deeps, which might temporarily improve the oxygen conditions and end anoxic states (e.g. Neumann et al., 2017).

Since the Baltic Sea is quite shallow, the dynamics are to a large extent wind-driven and variations in temperature, salinity and oxygen are closely linked to the prevailing atmospheric conditions. The climate of the Baltic Sea region is strongly related to the atmospheric large-scale circulation. In particular, the North Atlantic Oscillation (NAO) has a large impact on the Baltic Sea climate (Hurrell, 1995). A positive (negative) phase of the NAO is characterized by a strengthened (diminished) near-surface pressure difference between the Icelandic Low and Azores High, with stronger (weaker) than normal westerly winds. Consequently, a positive NAO is associated with warm and humid winters and a negative NAO with cold and dry winters over the Baltic area (BACC I Author Team, 2008). The influence of the NAO on the Baltic Sea can be observed in many different factors. Hänninen et al. (2000) showed a relationship between the NAO and river runoff to the Baltic Sea: a positive phase of the NAO is related to increased runoff, followed by a decrease in the mean salinity. Their results are confirmed by Zorita and Laine (2000), who studied the dependence of salinity and oxygen concentrations in the Baltic Sea on large-scale atmospheric circulation. They observed decreased salinities at all depths and enhanced oxygen conditions during strong meridional sea level pressure gradients over the North Atlantic. Andersson (2002) and Lehmann et al. (2002) presented a correlation between the NAO and changes in the Baltic sea level, and corresponding volume exchange with the North Sea, respectively.

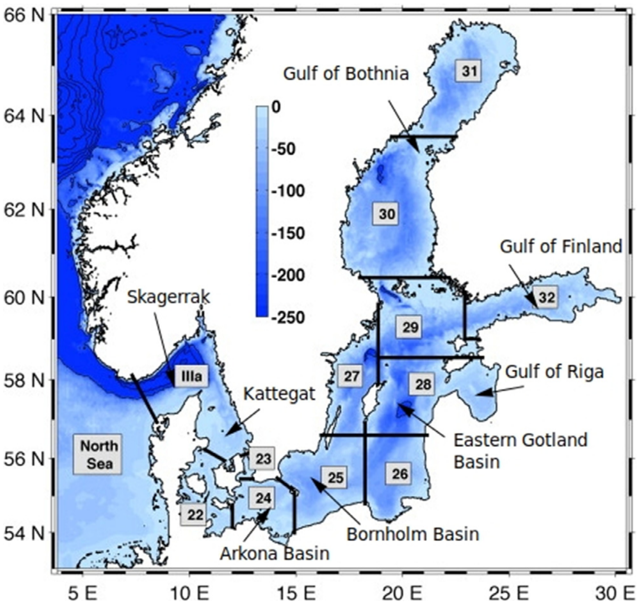

Figure 1 The Baltic Sea region with ICES subdivisions (with small modifications from Lehmann et al., 2014). Color scale shows sea depth in m.

The aim of this study is to provide a detailed investigation of changes in temperature, salinity and oxygen on different time and space scales in the Baltic Sea for the period 1950 to 2020. The main questions we would like to address are: Which variability and trends can be identified in the three parameters during this period of 71 years? And to what extent can the observed variations be explained by the influence of the atmosphere and river runoff? The former is analyzed by comparing observational data with the output of a numerical circulation model of the Baltic Sea. The data sets provide a sufficiently long period to investigate variability not only on annual and interannual but also on decadal time scales and allow validation of the results through comparison. Although many publications have analyzed variations in the hydrography of the Baltic Sea (e.g. BACC I Author Team, 2008; BACC II Author Team, 2015; Kniebusch et al., 2019a,b; Liblik and Lips, 2019; Meier et al., 2022), few studies have investigated variations of temperature, salinity and oxygen over this long period in such detail.

A detailed description of the data and methods used in this study is presented in the following section. The subsequent results section consists of two parts: First, the variations of temperature, salinity and oxygen in the Baltic Sea are described. In the second part, the atmospheric influence on the Baltic Sea hydrography is analyzed. Thereafter, the results are discussed in Section 4 and the paper ends with a short conclusion.

2. Data and methods

2.1. ICES data set on ocean hydrography

In this study, data sets of temperature, salinity and oxygen from the International Council for the Exploration of the Sea (ICES) oceanographic database were used as observational data (ICES, 2022). The data sets consist of a collection of CTD (Conductivity-Temperature-Depth) and bottle measurements from the entire Baltic Sea, spatially averaged across the ICES subdivisions (SD, see Figure 1) and aggregated to monthly means with a vertical resolution of 5 m stratum. It must be noted that the quality of spatially and temporally averaged values may differ in the individual months and subdivisions, depending on how many measurements were available. Furthermore, negative oxygen is not present in the ICES data set. The first measured values listed in the ICES data sets date from the end of the 19th century. However, there are large gaps in the data, especially at the beginning of the time series, as there are no measurements for some years and months. Good data coverage is given in most SDs from the 1950s or 1960s onwards. In the Gulf of Bothnia (SD 30 and 31), the Gulf of Riga and the Gulf of Finland (SD 32), there are large data gaps until the end of the 1970s (Liblik and Lips, 2019), especially in winter, because ice coverage makes measurements during the sea ice season which lasts on average from January to April (Leppäranta and Myrberg, 2009) difficult. This might have an impact on the trend estimations which we discuss further below. We used linear interpolation along the depth and time axes to close smaller data gaps. For each subdivision, we checked individually from which year onwards sufficient data are available to make linear interpolation reasonable. Particular care was taken to ensure that annual cycles in temperature and oxygen time series are well represented. As a rule, the gaps were not allowed to be larger than three consecutive months. Since the data coverage in the individual subdivisions varies, the prepared time series are of different lengths. The longest period is from 1956 to 2018 for the Arkona Basin (SD 24), the Bornholm Basin (SD 25) and the southeastern Baltic Proper (SD 26) and the shortest period is from 1977 to 2018 for the Gulf of Bothnia (SD 30 and 31) and the Gulf of Finland (SD 32). Finally, we applied a 3-month filter (moving average) to reduce noise and irregularities in the data.

2.2. Baltic Sea model output

Parallel to the observational data, the output of the three-dimensional coupled sea ice-ocean model of the Baltic Sea (BSIOM, Lehmann et al., 2002; Lehmann and Hinrichsen, 2000) was analyzed and both data sets were compared with each other. The Baltic Sea model has currently a horizontal resolution of 2.5 km, and the vertical structure is described by 60 layers, which allows resolving the upper 100 m with layers of 3 m thickness and layers of 6 m thickness below (Lehmann et al., 2014). The model covers the entire Baltic Sea, including the Kattegat and Skagerrak. At the western boundary, a simplified North Sea basin is connected to the model domain to provide characteristic temperature and salinity profiles in case of inflow situations from the North Sea into the Skagerrak. Outflowing water leaving the model domain will be slowly relaxed at the surface to typical North Sea salinity conditions. The model is further forced by low-frequency sea level variations in the North Sea/Skagerrak calculated from the BSI (Baltic Sea Index, Lehmann et al., 2002).

Table 1 Considered time periods and depths of surface layer, halocline and bottom layer for the selected ICES subdivisions.

	Considered time period	Surface layer [m]		Halocline depth [m]		Bottom layer [m]	
		ICES	BSIOM	ICES	BSIOM	ICES	BSIOM
Arkona Basin (SD 24)	1956—2018	0—10	1.5—10.5	30—40	31.5—40.5	40—45	40.5—46.5
Bornholm Basin (SD 25)	1956—2018	0—10	1.5—10.5	50—60	49.5—58.5	80—90	82.5—91.5
Eastern Gotland Basin (SD 28)	1959—2018	0—10	1.5—10.5	65—75	52.5—61.5	230—240	228—240
Gulf of Finland (SD 32)	1977—2018	0—10	1.5—10.5	60—70	61.5—70.5	—	—

The hydrodynamic model is realistically forced using the ERA5 global re-analysis in the preliminary extension version back to 1950 (Bell et al., 2021), with a 3-hourly temporal and approximately 50 km spatial resolution, respectively. The forcing data were interpolated on the model grid. They include surface air pressure, precipitation, cloudiness, and air- and dew point temperatures at 2 m height from the sea surface. Wind speed and wind direction at 10 m height from the sea surface were calculated from geostrophic winds with respect to different degrees of roughness on the open sea and off the coast (Bumke et al., 1998). BSIOM forcing functions, such as wind stress, radiation and heat fluxes were calculated according to Rudolph and Lehmann (2006).

In addition, river runoff is included in a monthly mean runoff data set provided by HELCOM Baltic Sea Environment Fact Sheets (Johansson, 2016). Oxygen uptake at the sea surface is determined from the oxygen saturation concentration using the modelled sea surface temperature and salinity values. The consumption of oxygen is modelled by one pelagic and two benthic sinks due to microbial and macrofaunal respiration (for details see Lehmann et al., 2014).

In this study, the output of the current model run from 1950 to 2020 is used. To obtain conditions as similar as possible to the observational data, the modelled temperature, salinity and oxygen values were spatially averaged across the whole area of the ICES subdivisions and monthly means were calculated. The time periods of the model data for each subdivision were adjusted to those of the ICES data for better comparability. Furthermore, we smoothed the data with a 3-month filter just like the observational data.

2.3. Analysis and comparison of ICES observational data and BSIOM data

The Baltic Sea is divided into 11 subdivisions according to ICES (Figure 1). Four specific subdivisions were selected and investigated for variations in temperature, salinity and oxygen: the Arkona Basin (SD 24), Bornholm Basin (SD 25), eastern Gotland Basin with the Gulf of Riga (SD 28) and Gulf of Finland (SD 32). Time series of temperature, salinity and oxygen were considered at three representative depth levels: at the surface, in the area of the halocline and at the bottom. For each depth level, the average was taken over a layer of about 10 m thickness. The depth of the halocline was determined using the 5%, 50% and 95% percentiles of salinity profiles (see Figure 2), visually estimating where the salinity gradient is strongest. The exact depths can be found in Table 1. In the Gulf of Finland, there is no permanent halocline at a specific depth. Instead, the presence and depth of the halocline vary with the prevailing inflow and wind conditions (Lehmann et al., 2022; Liblik and Lips, 2017; Stoicescu et al., 2019). Therefore, after averaging the data, the halocline is not visible in the percentiles in Figure 2.

On the annual time scale, mean annual cycles of temperature, salinity and oxygen were calculated for each subdivision and the three depth levels (surface, halocline, bottom) over the entire period (see Table 1 for the considered period in each subdivision). Time series of the monthly mean values with subtracted mean annual cycles were created to analyze the variability on longer than annual time scales. Linear trends were recalculated at all depths for the entire period using linear regression. To examine whether the time series showed variability on decadal time scales, a 10-year window trend was calculated using a moving average. Pearson correlation coefficients between the time series based on ICES and BSIOM data were determined to examine the agreement between the two data sets. For all correlation calculations, the annual cycles and linear trends of the time series were removed beforehand. Trend values and Pearson correlation coefficients in the present work were considered significant when the p-value was ≤ 0.05.

2.4. Investigation of the atmospheric influence on the hydrography of the Baltic Sea

The second part of this study deals with the influence of the atmosphere on the hydrography of the Baltic Sea. It is investigated whether the variations in temperature, salinity and oxygen can be related to changes in atmospheric parameters. For this purpose, the 2 m air temperature, zonal wind speed at 10 m height and precipitation from the ERA5 reanalysis data set (see Section 2.2) were used. Like the hydrographic data, the atmospheric parameters have also been averaged over the ICES subdivisions and to monthly mean values beforehand. Time periods of the ERA5 data were adjusted to those specified by the ICES data for each subdivision (see Table 1). Time series with anomalies from the annual cycle of air temperature were compared and correlated with sea surface temperature anomalies based on ICES and BSIOM data. Additionally, linear trends for the air temperature were calculated.

The impact of freshwater inflow was investigated using river runoff data provided by HELCOM (Johansson, 2016), which is also used as forcing in the Baltic Sea model. The

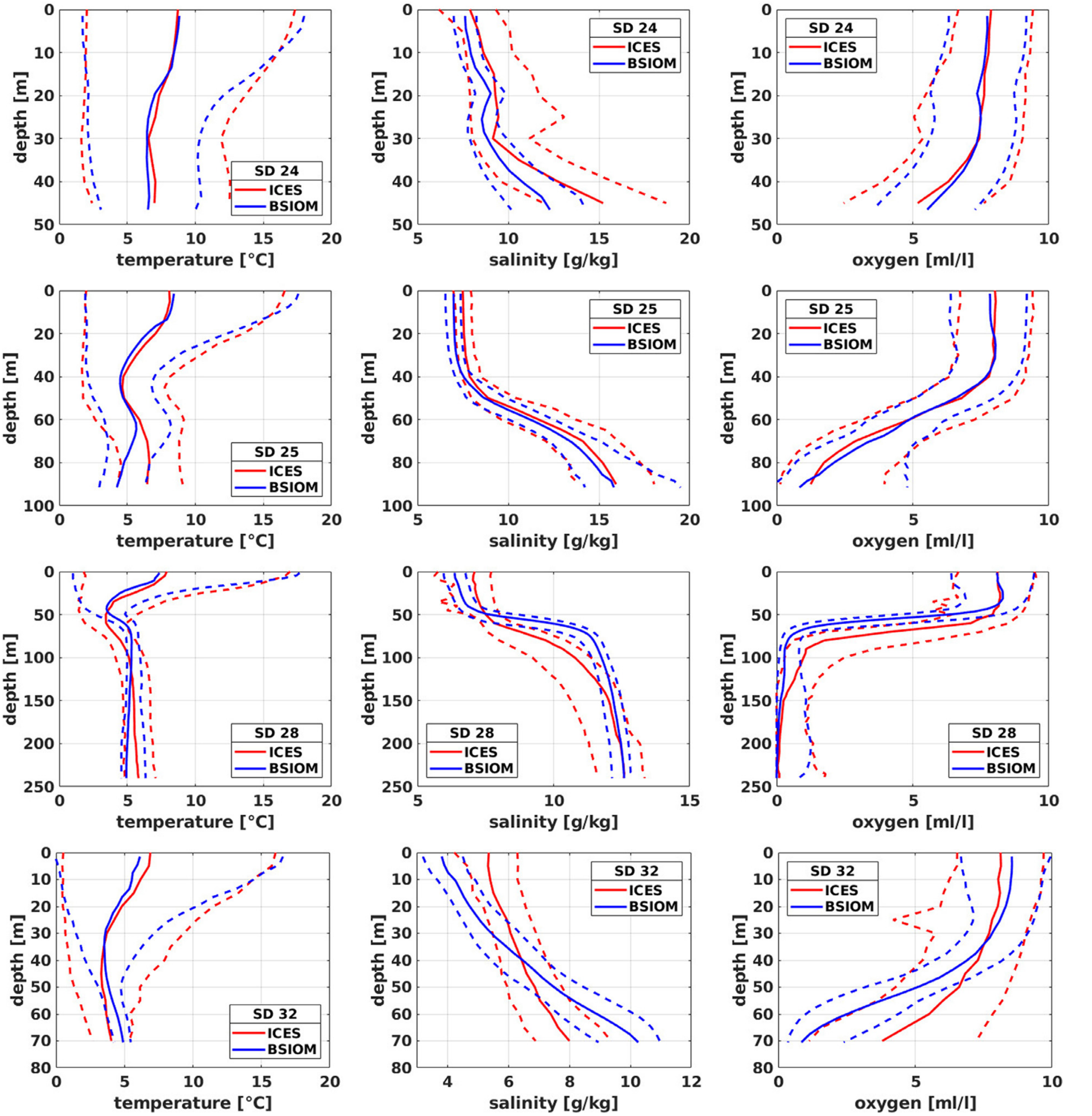

Figure 2 Percentiles (5% and 95%: dashed line, 50%: solid line) of temperature, salinity and oxygen profiles for SD 24 (period 1956–2018), SD 25 (period 1956–2018), SD 28 (period 1959–2018) and SD 32 (period 1977–2018) based on monthly means of ICES observational data and BSIOM model output. The monthly mean data are filtered with a 3-month moving average.

data set contains the sum of river discharge into the entire Baltic Sea and was used here with a temporal resolution of annual mean values. Furthermore, the data were accumulated and smoothed with a 5-year moving average to relate them to variations in salinity.

Finally, the influence of the NAO on the atmospheric and hydrographic parameters was examined. The winter DJF NAO index by Tim Osborne (updated from Jones et al., 1997) was used for this purpose. Correlation coefficients were calculated between the DJF NAO index and atmospheric and hydrographic parameters, which have been averaged over DJF and detrended beforehand.

3. Results

3.1. Trends and variability of temperature, salinity and oxygen

Figure 2 provides an overview of the range of variability in temperature, salinity and oxygen for the subdivisions 24, 25, 28 and 32 over the considered time periods. As depicted in the 5% and 95% percentiles, the range in which 90% of the observed and modelled values are located can be identified along the entire depth profile. The strongest fluctuations can be observed in temperature (Figure 2 left panels), especially in the top 20–30 m of each subdivision. Values here vary approximately between 0°C and 20°C which is caused by the annual cycles in SST. Comparing the temperature percentiles based on ICES data with those based on BSIOM output (Figure 2, left panels), it is noticeable that both the mean depth profiles and the ranges of variability coincide very well in all subdivisions.

The stratification of the water column is clearly visible in the salinity profiles (Figure 2 middle panels). In the upper layer, the salinity is in the range of approximately 4–8 g kg^{-1}, with decreasing values along the path from SD 24 to SD 32. Much higher salinities can be found at the bottom with up to 20 g kg^{-1} in the Arkona and Bornholm Basin. A strong salinity gradient between these two layers marks the depth of the halocline. In the Arkona Basin, the halocline is shown at a depth of about 30–40 m. Here, the increase in salinity gradient is somewhat more pronounced in the ICES data than in the model. For the Bornholm Basin (SD 25), the salinity profiles of the ICES and BSIOM data are in very good agreement. The halocline can be identified in this SD at a depth of 50–60 m. In SD 28, the location of the halocline in the model is slightly higher than in observation. It is located at a depth of about 50–60 m in the model and 65–75 m in the observations.

In all subdivisions, the layer above the halocline is nearly homohaline, while salinity in the lower layer continues to increase with depth. Fluctuations in salinity at the surface and in the area of the halocline are very small compared to variations in temperature and oxygen in all subdivisions. The 5% and 95% percentiles are close together in these areas and differ by a maximum of about 1–2 g kg^{-1} (except in the Arkona Basin, where the range of variation can also be larger). In SD 24 and 25, the percentiles fan out at the bottom. Here, variations in salinity are dictated by irregular inflows of highly saline water from the North Sea in combination with subsequent periods of stagnation.

Oxygen profiles (Figure 2 right panels) reflect the stratification defined by salinity. Above the halocline, the oxygen content is highest and almost constant with depth in all subdivisions. However, the absolute values can vary here in the range of 6–10 ml l^{-1}, which is related to the annual cycles in oxygen at the surface. The variability is less pronounced in the area of the halocline, while the 5% and 95% percentiles fan out again at the bottom due to inflow events. Mean profiles and variability ranges of oxygen are captured very well by the Baltic Sea model. Especially in SD 24 and 25, the percentiles based on ICES and BSIOM data match almost perfectly. In the Gulf of Finland, the observed bottom oxygen concentrations seem to be higher than the modelled.

A comparison between the observational data and model output for the temporal evolution of temperature, salinity and oxygen profiles for subdivisions 24, 25, 28 and 32 are presented in Appendix A (Figure A1 to Figure A4). These figures clearly show the annual cycles in temperature and oxygen at the sea surface. Furthermore, the varying depth of the halocline and the associated 2-layer structure of the water column can be seen (Figure A2 and Figure A3). The distribution and temporal development of temperature, salinity and oxygen are well captured by the model. Irregular major Baltic inflows (e.g. 1970, 1976, 1993, 2003 and 2014–2016), which are accompanied by a strong increase in salinity, but also changes in temperature and oxygen, are represented in both, observations and Baltic Sea model data.

In the following, we take a closer look at the trends and variations of temperature, salinity, and oxygen. It should be noted that the calculated trends from the observational data can be easily biased by missing observations at the beginning of the period. We calculated the trends for both observational and model data and found significant deviations in some cases. Therefore, in the following text, we mainly focus and rely on model-based trends.

3.1.1. Trends and variations in temperature

The time series of sea surface temperature with the mean annual cycle subtracted (Figure 3) show high interannual variability for the whole Baltic Sea. In some months the monthly mean temperature deviates from the mean annual cycle up to ±4°C (Figure 3, upper panel). To see how well the presented variations based on ICES and BSIOM data agree, correlation coefficients were determined. For the 3-month filtered SST data, the coefficients range from 0.68 in the Gulf of Finland to 0.87 in the Arkona and Bornholm Basin. Therefore, the data sets agree very well at the surface and the correlations are even better when annual averages of the SSTs are formed ($r = 0.9$ to 0.96).

Linear trends of SST are significantly positive in all subdivisions considered (see Table 2). Annual mean SST has increased with a rate of about 0.3°C $decade^{-1}$ in SD 24, SD 25 (period 1956–2018) and SD 28 (period 1959–2018), and with a higher rate of 0.4°C $decade^{-1}$ in the Gulf of Finland. For SD 32, however, it is important to take the shorter time period (1977–2018) into account. Warming trends of annual mean SST based on ICES observational data and BSIOM output coincide well. Linear trends over seasonally averaged sea surface temperature show stronger warming in summer than in winter (Table 2).

The 10-year window moving average of SST (Figure 3, upper panel) indicates that the warming trend is not constant over the entire period. In SD 24, SD 25 and SD 28, no distinct warming is evident in the first 25 years of the period. A continuous increase in SST can only be identified from about 1984 onwards. This is shown by observational data as well as in the Baltic Sea model. The correlation coefficients between the 10-year filtered data are high ($r = 0.8$ to 0.9). While the variability and linear trends of sea surface temperature are quite similar in all four subdivisions, there are differences between the basins in the remaining depth profile. In the Arkona Basin, the interannual variability of temperature after removing the annual cycle is still high down to the bottom. A different pattern of temperature variations is formed at the bottom of the Bornholm and Gotland Basin. There is less interannual variability, but irregular peaks in temperature associated with inflow events (Figure 3, lower panel). This can be observed particularly well with the BSIOM output, which shows weaker variations.

In general, the correlations between ICES and BSIOM data at the bottom of SD 25 and 28 are lower than at the surface ($r \approx 0.4$). In the Gotland Basin, the temperature fluctuations at the bottom are even smaller and less frequent than in SD 25, which can be seen both in the observation and in the model (see Figure A3). Interannual variability dominates again at the bottom of the Gulf of Finland, which is more pronounced in the ICES data than in the BSIOM data.

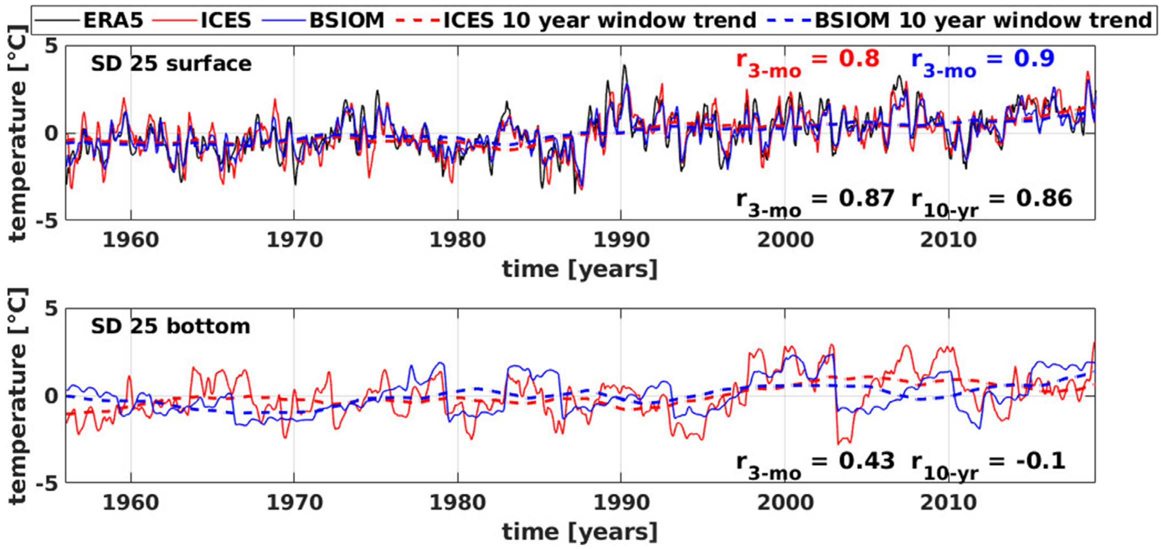

Figure 3 Anomalies from the annual cycle of 2 m air temperature (solid, black), sea surface and bottom temperature based on 3-month filtered ERA5 data, ICES observational data (solid, red) and BSIOM model output (solid, blue) for SD 25 and the period 1956—2018. Dashed lines show the 10-year moving average. Correlation coefficients are given for the correlation between 3-month ($r_{3\text{-mo}}$) and 10-year ($r_{10\text{-yr}}$) filtered BSIOM & ICES data, and between 3-month filtered ICES & ERA5 data ($r_{3\text{-mo}}$, red) and BSIOM & ERA5 data ($r_{3\text{-mo}}$, blue).

Table 2 Linear trends of SST (0—10 m) and 2 m air temperature in [°C decade^{-1}] for annual and seasonal (DJF, MAM, JJA, SON) means over the entire period. See Table 1 for the considered periods of each subdivision. SST trends are based on ICES observational and BSIOM model data, air temperature trends are based on ERA5 data. * indicates trends that are not statistically significant (5% level).

		Annual mean	DJF	MAM	JJA	SON
Arkona Basin (SD 24)	ICES	0.36	0.09*	0.41	0.62	0.29
	BSIOM	0.25	0.23	0.33	0.27	0.16
	ERA5	0.34	0.33	0.42	0.3	0.29
Bornholm Basin (SD 25)	ICES	0.3	0.11*	0.41	0.45	0.22
	BSIOM	0.27	0.23	0.34	0.34	0.17
	ERA5	0.33	0.33	0.38	0.32	0.26
Gotland Basin (SD 28)	ICES	0.28	0.13	0.26	0.46	0.28
	BSIOM	0.28	0.24	0.28	0.34	0.26
	ERA5	0.33	0.37	0.34	0.34	0.3
Gulf of Finland (SD 32)	ICES	0.39	0.18*	0.24	0.53	0.57
	BSIOM	0.4	0.25	0.25	0.54	0.52
	ERA5	0.62	0.76	0.6	0.64	0.47

Temperature trend profiles are presented in Figure 4. It is noticeable that all temperature trend profiles lie above zero. This means that the entire water column in the Baltic Sea is warming. However, the warming is mostly not homogeneous throughout the water column. All subdivisions have in common that temperature trends are strongest at the surface and tend to decrease with depth. In the Arkona Basin, BSIOM data show a trend of about 0.3°C decade^{-1} at the surface which decreases to about 0.2°C decade^{-1} below. In the Gotland and Bornholm Basin, a layered structure is shown in the ICES data with a trend minimum above the halocline (at about 40 m depth) and a maximum at the depth of the halocline itself (at about 60 m depth). The data thus indicate that warming is strongest at the surface and in the area of the halocline and lowest above the halocline and at the bottom. A deviating structure is shown by the model in SD 25 and 28 because the BSIOM data have a minimum temperature trend in the area of the halocline. At the bottom, however, the simulated and observed trends coincide very well again with rates of 0.25°C decade^{-1} in SD 25 and 0.15°C decade^{-1} in SD 28. The Gulf of Finland has a similar trend structure to that in the Arkona Basin. Temperature trends decrease from 0.5°C decade^{-1} at the surface to 0.2°C decade^{-1} at the bottom. There is no seasonality in temperature trends in the deep layer in most of the areas.

3.1.2. Trends and variations in salinity

At the surface, the interannual variability of salinity is very low. This is especially true for the Bornholm and Gotland Basin and the Gulf of Finland (Figure 5, upper panel). Correlations between ICES and BSIOM surface salinity are weaker than those observed in sea surface temperature in all sub-

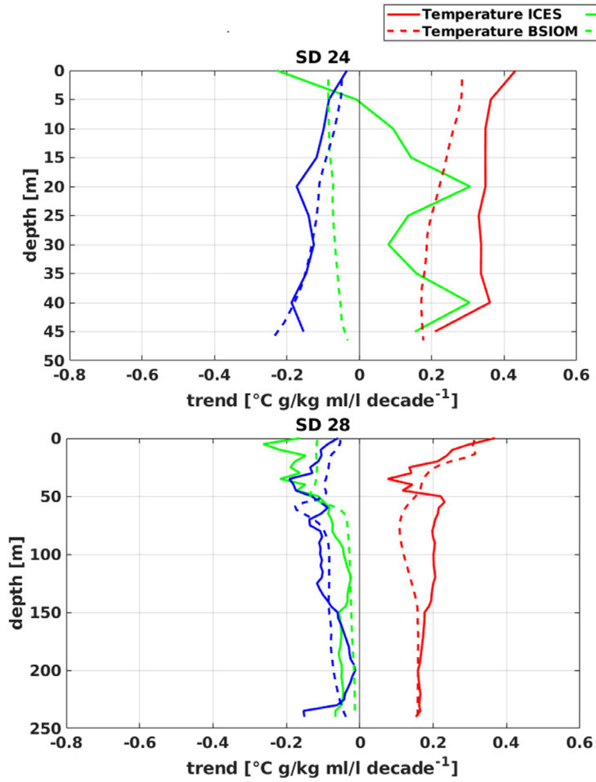

Figure 4 Trends per decade of temperature, salinity and oxygen for SD 24 (period 1956–2018), SD 25 (period 1956–2018), SD 28 (period 1959–2018) and SD 32 (period 1977–2018) based on ICES observational data (solid line) and BSIOM model output (dashed line).

divisions. Correlation coefficients are between 0.4 and 0.5 for the 3-month filtered data as well as for the annual mean data in SD 24 and SD 32. The data sets in SD 25 and 28 agree much better (see Figure 5, upper panel). Here, the correlation coefficients are 0.68 and 0.76 for the 3-month filtered surface salinity and between 0.8 and 0.9 for annual mean values.

A decrease in salinity at the surface can be observed in all subdivisions (Table 3). Linear trends over the entire period show a significant decrease of 0.05–0.08 g kg^{-1}

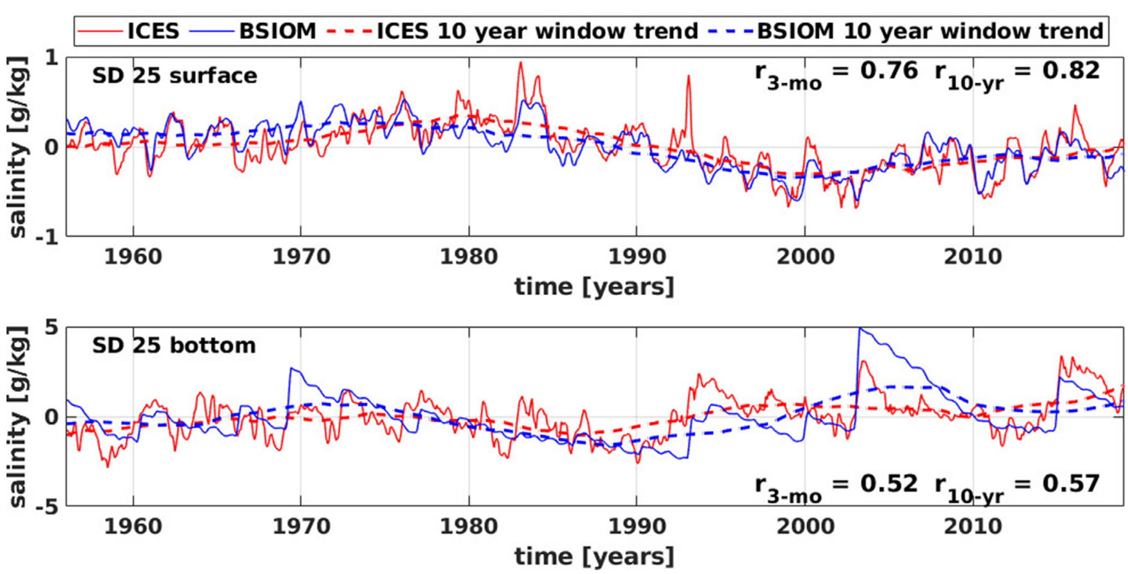

Figure 5 Anomalies of surface salinity (upper panel) and bottom salinity (lower panel) based on 3-month filtered ICES observational data (solid, red) and BSIOM model output (solid, blue) for SD 25 and the period 1956–2018. Dashed lines show the 10-year moving average. Correlation coefficients are given for the correlation between 3-month ($r_{3\text{-mo}}$) and 10-year ($r_{10\text{-yr}}$) filtered BSIOM & ICES data.

Table 3 Linear trends of surface salinity (0—10 m) in [g kg^{-1} decade^{-1}] for annual and seasonal (DJF, MAM, JJA, SON) means over the entire period. See Table 1 for the considered periods of each subdivision. * indicates trends that are not statistically significant (5% level).

		Annual mean	DJF	MAM	JJA	SON
Arkona Basin (SD 24)	ICES	−0.05	0.07*	−0.08	−0.12	−0.07
	BSIOM	−0.08	−0.07	−0.08	−0.1	−0.08
Bornholm Basin (SD 25)	ICES	−0.06	−0.06	−0.06	−0.06	−0.06
	BSIOM	−0.08	−0.08*	−0.08	−0.08	−0.09*
Gotland Basin (SD 28)	ICES	−0.21	−0.14	−0.25	−0.28	−0.19
	BSIOM	−0.12	−0.11	−0.11	−0.12	−0.12
Gulf of Finland (SD 32)	ICES	−0.21	−0.19	−0.18	−0.22	−0.26
	BSIOM	−0.03	−0.02*	−0.02*	−0.02*	−0.03*

decade^{-1} in the Arkona and Bornholm Basin. The trends based on the Baltic Sea model and the observational data match closely here. As can be seen in Table 3, the negative salinity trends prevail in all seasons and no significant differences in the seasonal cycle are pronounced in SD 24 and SD 25. In the eastern Gotland Basin, the model shows stronger freshening trends of 0.12 g kg^{-1}, but no significant freshening is visible in the Gulf of Finland from BSIOM data. The ICES data show a much stronger freshening in these areas. However, this might be an artificial signal due to the irregularity in the data.

The 10-year moving average of surface salinity anomalies (Figure 5, upper panel) shows a pronounced decadal variability in SD25. This can also be observed in SD 24 and SD 28 (not shown). Increasing salinities can be seen from the beginning of the period until the end of the 1970s and early 1980s in these areas. Thereafter, the surface salinity decreases until about 2000, where a minimum is shown in SD 25, SD 28 and in the BSIOM data of SD 24. Since then a slight increase in the data can be observed again. In the Bornholm and eastern Gotland Basin, the 10-year window trends based on ICES data correlate very well with those based on BSIOM output ($r = 0.82$ for SD 25 and $r = 0.9$ for SD 28). In the Gulf of Finland, the 10-year filtered ICES surface salinity data show a permanent decrease throughout the period, which is more pronounced at the beginning until about 1990.

In the area of the halocline of SD 25 and 28, the 10-year window trend of salinity shows a strongly declining salinity from 1980 onwards with a striking minimum around 1992. This minimum is also clearly depicted in the salinity profiles of Figure A3. At the bottom, strong peaks of salinity due to major inflow events can be observed at irregular intervals in SD 25 and 28 (Figure A2, Figure A3, Figure 5 lower panel). Particularly strong inflow events can be observed e.g. in 1970 and 2003, where the salinity anomaly is quickly raised by up to 5 g kg^{-1} in the deep layer of the Bornholm Basin. There is a complete lack of strong salinity peaks between 1983 and 1993. The Baltic Sea model shows fewer salinity inflows than the ICES data in the Bornholm and Gotland Basin. However, the particularly strong inflow events are represented very closely by the model.

Both data sets indicate a decadal variability of large saltwater inflows with a period of about 30 years through their 10-year moving average in SD 25 (see Figure 5, lower panel) and SD 28. However, the investigated time period is too short to conclude a regular variability with such a period. A similar pattern can be observed in the 10-year moving averaged bottom salinity of the Gulf of Finland. Here, however, it is not the irregular peaks due to major inflows that dominate the deep layer salinity, but a pronounced interannual variability (Figure A4). In the Arkona Basin as well, interannual salinity variations at the bottom are high and the decadal variability, on the other hand, is very weak.

From the salinity trend profiles in Figure 4, it becomes clear that the long-term trends behave differently at the bottom than at the surface. While declining salinity trends can be observed in the upper layer, the tendency in the deep layer is towards positive trends. The difference is most obvious in the Bornholm Basin. Below the halocline, there are significant positive trends of about 0.2 g kg^{-1} decade^{-1}. In the Gotland Basin and the Gulf of Finland, no increase in the deep layer salinity can be observed over the entire period, but trends are almost zero. The ICES and BSIOM salinity trend profiles in the Arkona Basin deviate from each other. While the Baltic Sea model shows a slight decrease throughout the entire water column, the observational data indicate an increase of salinity in the lower 40 m of the basin with maxima at 20 m and 40 m depths.

3.1.3. Trends and variations in oxygen

From Figure 6, a strong interannual variability of oxygen is noticeable in all subdivisions at the surface. Correlations between surface oxygen anomalies based on BSIOM and ICES data are highest in the Arkona and Bornholm Basin ($r \approx 0.6$, see Figure 6). In SD 28 and SD 32, the time series are less consistent ($r_{SD28} = 0.45$ and $r_{SD32} = 0.2$).

Table 4 shows a significant decrease in surface oxygen concentrations in the entire Baltic Sea over the period under consideration. Linear trends lie between −0.05 and −0.08 ml l^{-1} decade^{-1} in all subdivisions. Seasonal trends demonstrate a higher decline in surface oxygen concentrations in summer (from June to August) than in winter (Table 4). No particular decadal variability is evident in the 10-year window trend of the surface oxygen anomalies (Figure 6, upper panel). Similar to that in temperature, the 10-year moving average is close to zero and nearly constant until the mid-1980s, and only from then on, a clear decline can be observed. This pattern applies to all subdivisions and both hydrographic data sets. Overall, the variability and trends in surface oxygen are similar to those of temperature, since both parameters are linked by the change in solubility depending on varying water temperature.

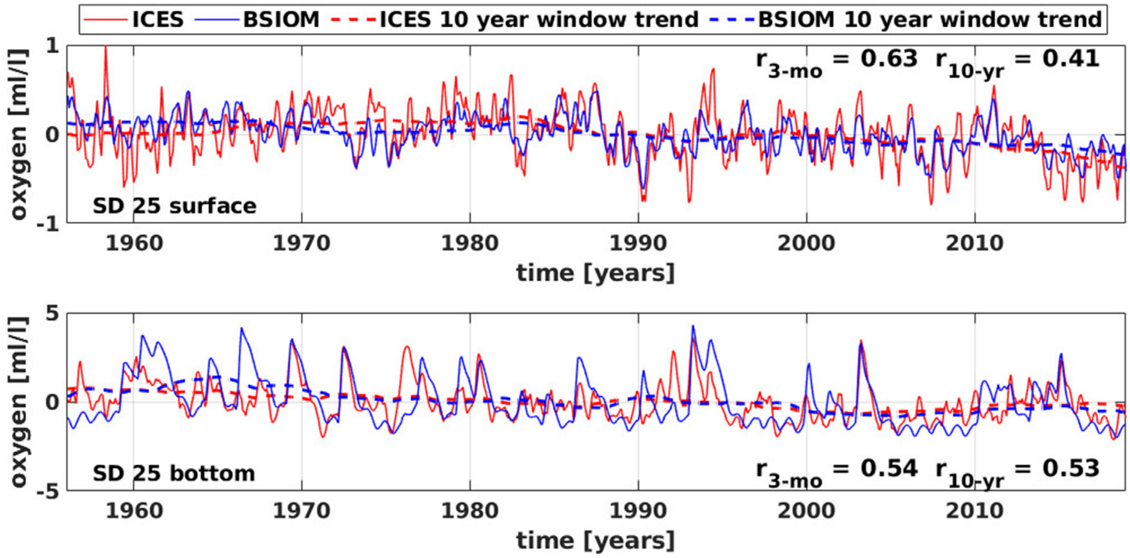

Figure 6 Anomalies of surface oxygen (upper panel) and bottom oxygen (lower panel) based on 3-month filtered ICES observational data (solid, red) and BSIOM model output (solid, blue) for SD 25 and the period 1956–2018. Dashed lines show the 10-year moving average. Correlation coefficients are given for the correlation between 3-month ($r_{3\text{-mo}}$) and 10-year ($r_{10\text{-yr}}$) filtered BSIOM & ICES data.

Table 4 Linear trends of surface oxygen (0–10 m) in [ml l^{-1} decade^{-1}] for annual and seasonal (DJF, MAM, JJA, SON) means over the entire period. See Table 1 for the considered periods of each subdivision. * indicates trends that are not statistically significant (5% level).

		Annual mean	DJF	MAM	JJA	SON
Arkona Basin (SD 24)	ICES	−0.07	0.02*	−0.07	−0.12	−0.05
	BSIOM	−0.05	−0.05	−0.07	−0.06	−0.03
Bornholm Basin (SD 25)	ICES	−0.05	0*	−0.08	−0.08	−0.03
	BSIOM	−0.05	−0.05	−0.07	−0.06	−0.03
Gotland Basin (SD 28)	ICES	−0.08	−0.05	−0.03	−0.15	−0.09
	BSIOM	−0.05	−0.05	−0.05	−0.06	−0.04
Gulf of Finland (SD 32)	ICES	−0.16	−0.14	−0.17	−0.21	−0.13
	BSIOM	−0.07	−0.05	−0.04	−0.09	−0.09

In the area of the halocline, variations of oxygen are stronger than at the surface. In addition to strong interannual variability, the 10-year moving average shows a pronounced minimum around 1970 and a maximum around 1990 in the Bornholm and eastern Gotland Basin. This pattern is similar to that of salinity in the same depth but reversed. It is also evident from the oxygen profiles in Figure A3.

At the bottom, there are large differences between the oxygen time series of the individual subdivisions: while interannual variations dominate in the Arkona Basin, only irregular fluctuations cause variations of oxygen in SD 25 and SD 28 (Figure 6, lower panel, Figure A1–A3), which can be related again to inflow events from the North Sea. Anomalies with peaks up to 4 ml l^{-1} can be observed with high frequency in the Bornholm Basin. Here, the BSIOM output shows more frequent fluctuations than the ICES observational data. For example, no marked fluctuations can be observed in the ICES data for the period 1980–1993, but there are some in the Baltic Sea model (Figure 6). This is reflected in the correlation coefficient between the two data sets, which is about 0.5 in the bottom oxygen in SD 25. However, both data sets have in common that the intensity and frequency of such oxygen anomalies have decreased since mid-1990. In the eastern Gotland Basin, the oxygen concentration at the bottom is zero most of the time (see Figure A3). Only a few inflows can raise the oxygen content here to about 2 ml/l for a short time (e.g. in 1970, 1993 and 2003). The Gulf of Finland shows a strong interannual signal in bottom oxygen concentration again. Just as in the area of the halocline of the other basins, the 10-year moving average has a pronounced maximum around 1990 at the bottom of SD 32.

The oxygen trend profiles (Figure 4) are negative in all subdivisions and across the entire water column. The decrease in oxygen is weakest at the surface and tends to increase with depth. At the bottom of the Arkona Basin, a decrease in oxygen up to −0.2 ml l^{-1} decade^{-1} can be seen. In SD 25, there is a maximum decrease with −0.3 ml l^{-1} decade^{-1} at 70 m depth. BSIOM data and ICES observations agree almost exactly here (Figure 4, upper right). A smaller maximum with about −0.2 ml l^{-1} decade^{-1} is shown in the eastern Gotland Basin at 40 m depth with the ICES data and at about 60 m with the BSIOM data. The strongest trend can be observed at about 60 m depth in the Gulf of Finland, where BSIOM data show an oxygen decrease up to −0.2 ml l^{-1} decade^{-1}. No remarkable seasonality is shown in the negative oxygen trends in the deep layer of the Baltic Sea.

3.1.4. Correlations between the variations in temperature, salinity and oxygen

In order to investigate more closely whether there are connections between the described variations in temperature, salinity and oxygen that indicate common forcing factors, the time series were correlated with each other. At the surface, strong anticorrelations were found between the 3-month filtered temperature and oxygen anomalies, which is not surprising due to their connection by solubility. This connection is particularly pronounced in the Baltic Sea model output with correlation coefficients of −0.98 in all subdivisions. The ICES data show slightly lower correlations ($r = -0.6$ to -0.7) between surface temperature and oxygen time series.

In the depth of the halocline, a particularly negative correlation ($r = -0.9$ in ICES and $r = -0.96$ in BSIOM data) between salinity and oxygen anomalies is noticeable in SD 28 and SD 32. Low salinities are associated with high oxygen concentrations and vice versa. This observation can be explained by the vertical movement of the halocline. Oxygen conditions deteriorate at a given depth as the halocline rises. In the Bornholm Basin, this relationship is also visible, but not that pronounced ($r = 0.5$ in ICES and BSIOM data).

3.2. Analysis of the atmospheric influence on the Baltic Sea hydrography

3.2.1. Impact of the air temperature

As can be seen in Figure 3, the air temperature anomalies from the annual cycle fit very precisely with the SST anomalies in SD 25 over the entire time period. The correlation coefficient between ICES SST and air temperature is 0.8, and 0.9 between BSIOM SST and air temperature in this basin, as well as in the Arkona Basin. In SD 28, the correlations are slightly lower and lowest in the Gulf of Finland with $r \approx 0.6$ between air temperature and ICES SST, and $r \approx 0.7$ with the BSIOM surface temperature. From the seasonally averaged time series of SD 32 (not shown), it becomes clear that the differences in sea surface and air temperature are particularly pronounced in winter (from December to February). Significantly higher correlations are determined with annual mean anomalies of the sea surface and air temperature. The correlation coefficients lie then predominantly between 0.9 and 0.98 in all subdivisions.

Table 2 shows that temperature trends in the period from 1950 to 2018 are very similar in the atmosphere and the sea surface in all subdivisions. The long-term trend of air temperature in the Arkona, Bornholm and eastern Gotland Basin for the period 1956/59–2018 is about 0.33°C decade^{-1} (see Table 2). A significantly stronger trend in air temperature is noticeable in the Gulf of Finland for the period 1977–2018. With a rate of 0.62°C decade^{-1}, the atmospheric warming is higher than observed in the water temperature in this area. Seasonally, the trend of air temperature is strongest from December to February in SD 32 (0.76°C decade^{-1}, see Table 2). Also in the eastern Gotland Basin, the strongest atmospheric warming takes place in winter (DJF). In SD 24 and SD 25, however, the maximum trends are observed from March to May. The trends are weakest in all subdivisions from September to November.

3.2.2. Impact of the freshwater inflow

Figure 7 (upper panel) shows the annual mean river runoff into the Baltic Sea. For the period 1959–2018, the total mean river discharge was 15.5×10^3 m^3 s^{-1}. No long-term trend can be observed in the runoff for this period, but there are alternating dry and wet periods lasting for a couple of years to a decade. Particularly wet periods can be observed between 1969 and 1976 or between 2002 and 2009 (orange ranges in Figure 7). The runoff was above the mean value during 1978–1990 and 1996–2002 (green ranges). When comparing the runoff time series with the volume averaged salinity of SD 28, we notice that salinity clearly decreased during periods with anomalous strong runoff and increased during dry periods. As described above, particularly strong saltwater inflow events followed by high peaks in the deep layer salinity of SD 28 could be observed in 1970 and 2003 (see Figure A3). These major Baltic inflows lie exactly in the periods with low runoff to the Baltic Sea and are responsible for the increase in average salinity from Figure 7. In contrast, no strong saltwater inflows were observed in the eastern Gotland Basin during the wet periods. In the 5-year filtered zonal wind speed (Figure 7, middle panel), positive anomalies can be observed during both the particularly wet and dry periods. Especially in the period 1979–1990, a strong increase in zonal wind speed is striking.

The observed influence of river runoff into the Baltic Sea on variations in salinity on decadal timescales is confirmed

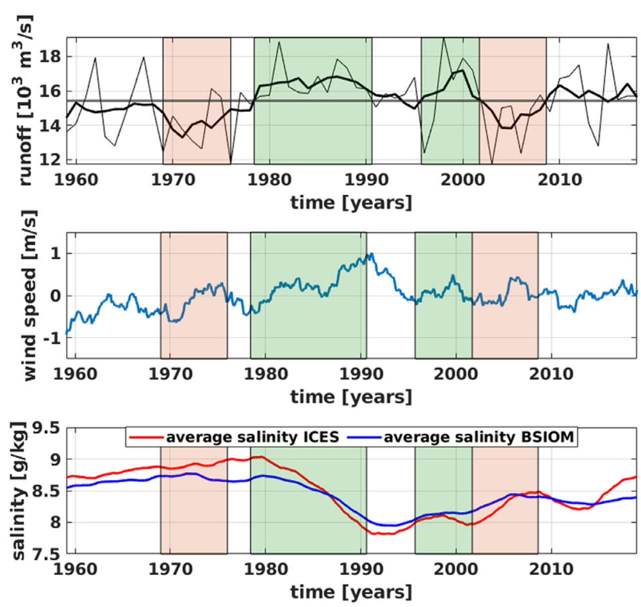

Figure 7 Upper panel: Annual mean river runoff to the Baltic Sea (thin line). In addition, the 5-year moving average (thick line) and the total mean for the period 1959–2018 (horizontal line) are shown. Middle panel: Zonal wind speed anomaly for SD 24 based on ERA5 data, smoothed with a 5-year moving average. Lower panel: Volume averaged salinity smoothed with a 5-year moving average based on ICES (red) and BSIOM (blue) data for SD 28. The green (orange) shaded ranges indicate periods with positive (negative) anomalous runoff.

Table 5 Correlation coefficients between accumulated anomalies of runoff to the Baltic Sea (inverted) and sea surface salinity and volume averaged salinity respectively. All-time series are smoothed with a 5-year moving average. * indicates correlations that are not statistically significant (5% level). Values with footnotes indicate higher correlations when a time lag is considered. The footnote represents the lag in years.

		SD 24		SD 25		SD 28		SD 32	
Surface salintiy	ICES	0.86		0.79		0.84		0.23*	
	BSIOM	0.59	0.67[3]	0.63	0.69[3]	0.80	0.81[2]	0.27*	
Volume averaged salinity	ICES	0.44		0.52	0.60[2]	0.71	0.81[3]	0.44	
	BSIOM	0.59	0.73[4]	0.55	0.78[4]	0.67	0.79[4]	0.48	0.50[1]

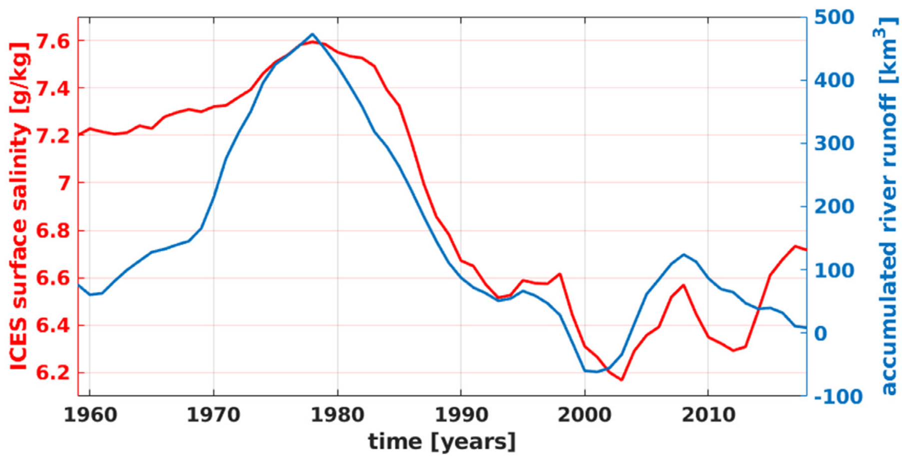

Figure 8 Sea surface salinity (0—10 m) filtered with a 5-year moving average of SD 28 for the period 1959 to 2018 based on ICES data and 5-year filtered accumulated anomalies of runoff of the Baltic Sea (inverted). The correlation coefficient is 0.84.

by correlation calculations. Correlation coefficients were determined between the accumulated runoff anomaly and the volume averaged and surface salinity of each subdivision (Table 5). For the volume averaged salinity, the correlation is highest in the eastern Gotland Basin ($r \approx 0.7$ when no lag is considered). It is remarkable that higher coefficients ($r \approx 0.8$) are obtained when a lag of 2—4 years is taken into account. Here, the runoff anomaly precedes the change in salinity and the correlations become significantly worse with a shift in the other direction. Even higher correlations can be seen between the accumulated river runoff anomaly and salinity at the surface. The relationship with surface salinity in the eastern Gotland Basin is illustrated in Figure 8. However, high correlation coefficients are obtained not only in SD 28 but also in the Arkona and Bornholm Basin at the surface (Table 5). In general, correlations with surface salinities based on the BSIOM model output are smaller than with the ICES data. Better correlation coefficients were obtained for the model data when a lag of 2—3 years was considered. Again, the runoff anomaly precedes the change in salinity. In the Gulf of Finland, there is no significant correlation between surface salinity and accumulated river runoff.

3.2.3. Impact of the NAO

The winter NAO index for the period 1956—2018 is presented in Figure 9. It is noticeable that positive and negative phases of the NAO alternate at irregular intervals of usually several years. First, direct correlations between the winter NAO index and variations in temperature, salinity and oxygen are investigated. Significant correlations are observed between the winter NAO index and sea surface temperature anomalies in SD 24, SD 25 and SD 28 (see Table B1). The coefficients range between 0.5 and 0.6 and decrease from the western to eastern basins. From Figure 9 it is clear that especially the positive NAO phases coincide well with positive temperature anomalies. A slightly weaker and negative correlation ($r \approx -0.4$ to -0.6) can be seen between the NAO index and the surface oxygen anomalies in these basins. An influence of the NAO on surface salinity can only be detected in the Arkona Basin (Table B1). Again, mainly the positive NAO phases are associated with increasing surface salinity in SD 24. The negative anomalies match less (see Figure 9).

In the surface layer of SD 32, no impact of the NAO is evident. The influence of the NAO is also not clear in the deeper layers of the Baltic Sea. Correlation coefficients are mostly low or not statistically significant. However, a striking pattern can be observed in the area of the halocline in SD 28 as well as at the bottom of SD 32 for the period from 1983 to the end of the 1990s: the positive NAO phases are associated with a strongly negative salinity and positive oxygen anomaly (see Figure B1). In the remaining period, this correlation is not clear, so the correlation coefficients are weak ($r = -0.3$ and $r = 0.3$ respectively).

In addition, the influence of the NAO on atmospheric parameters over the Baltic Sea in winter was investigated (not shown). The impact on the temperature in 2 m height and zonal wind speed is very pronounced. Positive (negative) NAO phases are associated with positive (negative) temperature and wind speed anomalies. The correlation coefficients are 0.7 for both temperature and zonal wind speed in

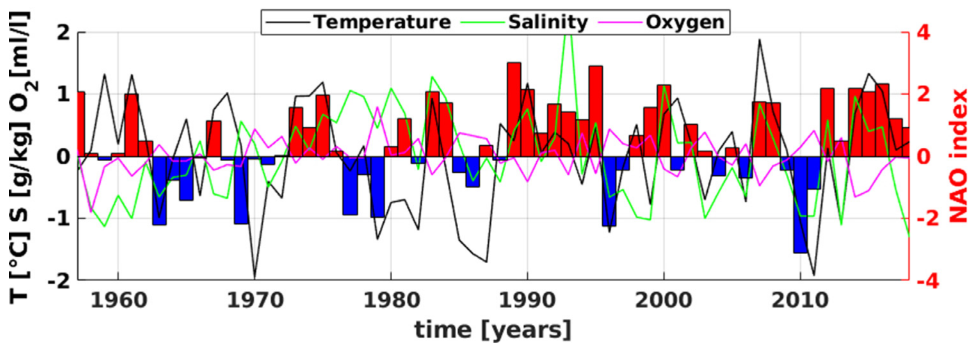

Figure 9 Winter (DJF) NAO index (bars) for the period 1956–2018 and DJF-mean temperature (black), salinity (green), oxygen (magenta) at the surface (0–10 m) based on ICES data for SD 24.

all subdivisions. For precipitation, the correlation is weaker: in the Bornholm Basin there is no statistically significant correlation at all, and the strongest relationship can be found in the Gulf of Finland ($r = 0.53$).

4. Discussion

In the present paper, we provide a detailed overview of the variations of temperature, salinity and oxygen in the Baltic Sea that can be observed in the period 1950 to 2020. The results of both hydrographic data sets investigated, ICES observational data and BSIOM model output, coincide well in the selected subdivisions. There are high interannual variations in sea surface temperature which closely follow variations in air temperature. On interannual time scales, the NAO strongly controls the variability of the sea surface and air temperature in winter. Linear trends over the period from 1950 to 2020 show significantly increasing sea surface and air temperatures of about 0.3 to 0.4°C decade^{-1} in all subdivisions studied. The trends are significantly stronger since the mid-1980s compared to the first half of the observation period. Increasing water temperatures can not only be observed at the sea surface but throughout the entire water column in the Baltic Sea. In salinity, pronounced variability on annual and decadal timescales is indicated during the period 1950 to 2020. Decadal variations of surface salinity are strongly controlled by the accumulated river runoff, which can explain about 70% of the variability. In the deep layer salinity, the decadal variability is associated with variations in saltwater import from the North Sea, which in turn are influenced by river runoff and the prevailing wind conditions. The long-term trends over the period 1950–2020 show a freshening of the upper layer and stagnating or increasing salinities in the deep layer of the Baltic Sea. This trend pattern in salinity is associated with a rising of the halocline and a strengthening of the stratification across the halocline. Surface oxygen depicts strong variations on annual and interannual timescales that are strongly anticorrelated with the SST due to solubility. Linked to the rising temperatures, the oxygen is significantly decreasing during the period 1950–2020 in the Baltic Sea with stronger trends since the mid-1980s. Additionally, eutrophication intensifies both the primary production of organic matter and oxygen consumption needed for its degradation (HELCOM, 2009; Lehmann et al., 2014b).

Trends and variations in temperature, salinity and oxygen for different time periods and regions of the Baltic Sea have already been the subject of several studies. High correlations between SST and air temperature in the Baltic Sea and a strong link with the NAO index in winter were also found by e.g. Bradtke et al. (2010), Janssen (2002) and Tinz (1996). The observed trends in sea surface temperature are consistent with earlier estimates as well: 0.3°C decade^{-1} in the southeastern Baltic Sea for the period 1960–2015 (Rukšėnienė et al., 2017) and 0.5°C decade^{-1} for the period 1982–2016 (Liblik and Lips, 2019). Calculations of SST trends from satellite measurements since the beginning of the 1980s show a greater increase in the northern areas of the Baltic Sea (i.e. Gulf of Bothnia, Gulf of Finland, northern Baltic Proper) than in the rest of the basin (Bradtke et al., 2010; Lehmann et al., 2011; Liblik and Lips, 2019). As noted by previous studies (e.g. Liblik and Lips, 2019; Stramska and Białogrodzka, 2015), the warming trends in SST are stronger in summer than in winter (Table 2). Furthermore, our results show that besides the surface, especially in and within the halocline a strong warming exists. This is probably related to the inflow of water from the North Sea that has also warmed at the surface. However, vertical movement of the halocline could also play a role.

Opposite salinity trends for the upper and deep layers of the Baltic Sea were also observed by Liblik and Lips (2019). For the period 1982–2016, they detected a freshening of the upper layer and increasing salinity in the deep layer of the Baltic Sea with comparable magnitudes. However, this trend pattern is not consistent with the findings of Zorita and Laine (2000), who reported a homogeneous evolution of salinity in the entire water column for the period 1962–1996. The contradictory results can be related to the different periods considered and the pronounced decadal variability in both the upper and lower layer salinity. As shown in this work, the decadal variability of the surface salinity is strongly linked to the accumulated river runoff (Table 5, Figure 8). Periods of increased river runoff are followed by lower surface salinities and vice versa.

The influence of river discharge on salinity in the Baltic Sea is the subject of numerous studies (e.g. Liblik and Lips, 2019; Meier and Kauker, 2003; Radtke et al., 2020; Winsor et al., 2001). Liblik and Lips (2019) cannot explain all the decadal variability of surface salinity by accumulated river runoff, since the two quantities do not correlate well in their observations between 2002 and 2009 (see their Figure 9). Instead, they suggest that decadal changes in vertical salt flux contribute as well. In our observations, however, the courses of accumulated river runoff and surface salinity match closely between 2002 and 2009 (Figure 8). This could indicate that vertical salt flux might play a smaller role in decadal surface salinity changes than assumed by Liblik and Lips (2019). However, further investigations are needed to clarify this question. As noted by Radtke et al. (2020), we can see the impact of river runoff not only on surface salinity but also on the occurrence of MBIs: strong inflow events occurred in periods of reduced river runoff and fewer in periods of enhanced runoff. High correlation coefficients between accumulated river runoff and volume-averaged salinity (Table 5) support this observation. It is noticeable that the correlations with volume-averaged salinity are higher when lags of 2–4 years are considered (runoff precedes salinity changes). The time lag confirms the indirect influence, since changes in deep layer salinity only occur when the inflow water from the Kattegat has spread along the topography.

Our results are furthermore in agreement with Meier and Kauker (2003), who explained about 50% of the decadal changes in mean salinity by accumulated runoff anomalies. However, they found that another significant part of the decadal variability of mean salinity is caused by the low-frequency variability of zonal wind speed. Enhanced zonal wind over the Baltic Sea is linked with intensified precipitation over the catchment and increased river runoff to the Baltic, and reduces the activity of strong saltwater inflows at the same time (Meier and Kauker, 2003). This connection is also indicated in our results (Figure 7), which show that zonal wind speeds over the Arkona Basin are exceptionally high during periods of increased runoff and decreasing mean salinity in the Baltic Sea. However, it is still unclear whether the changes in saltwater inflow activity are related to changes in runoff, or whether an atmospheric pattern can be identified that influences river runoff and inflow activity independently.

We further observed that the zonal wind speed over the Baltic Sea is strongly controlled by the NAO (Table B1). This suggests that the NAO also has an influence on the volume exchange with the North Sea. However, correlations between the winter NAO index and salinity anomalies in the Baltic Sea are mostly not clear in our observations. Lehmann et al. (2002) studied the impact of NAO on water exchange with the North Sea (independent of the salinity of the water) and found a clear relation: a high positive phase of the NAO is related to increased inflows into the Baltic Sea and a negative NAO favours outflow conditions. In this case, it is important to note that inflow into the Baltic Sea does not only mean major Baltic inflows, which increase the bottom salinity in the Baltic Sea but also inflows with lower salinity, which cannot be detected in our salinity time series. This could explain why we have difficulties in identifying the influence of the NAO on salinity changes in the Baltic Sea.

As also noted by Zorita and Laine (2000), we observed decadal variability in oxygen in the area of the halocline of the Bornholm and eastern Gotland Basin and at the bottom of the Gulf of Finland, which is strongly anti-correlated to the decadal variability in salinity in these areas. There is a pronounced minimum in salinity around 1990 in these areas, which can be linked to the absence of MBIs during 1983–1993 and the associated weakening of the halocline. In the Gulf of Finland, the halocline vanished completely during this time. Due to mixing, oxygen-rich water from the upper layer can then reach greater depths. However, since the 1990s, salinity increased again in these areas, which has resulted in a strong oxygen decrease in the last decades. Maximum negative trends up to -1 ml l^{-1} decade^{-1} in the area of the halocline (eastern Gotland Basin) have also been reported by Lehmann et al. (2022).

For the assessment of the results, it is important to briefly point out the main limitations or uncertainties of both data sets. The Baltic Sea model has a limited horizontal (2.5 km) and vertical resolution (3 m), and approximations (e.g. hydrostatics, incompressibility) are applied in the model. Accordingly, the simulation of vertical mixing processes is restricted, which could be a reason for the underestimated depth of the halocline by BSIOM in the eastern Gotland Basin and for differing structures in the trend profiles. Furthermore, we observed fewer salinity peaks at the bottom of SD 28 with BSIOM data (Figure A3), suggesting that the exact spread of water masses in the deep layer is difficult to model. The simplified bottom topography of the model could play a role here. A relatively simple approach is used for modelling oxygen consumption in the water column, which does not resolve the complex biogeochemical cycle. Nevertheless, the variability and distribution of oxygen overall are well represented by the Baltic Sea model. The ICES observational data, on the other hand, do not correspond exactly to reality either. Data density in individual months and subdivisions can vary greatly. The data are more representative if there are many measurements in a month, which were taken over the entire subdivision and not only at a few stations. Especially in the northern subdivisions, it must be assumed that fewer measurements were taken in winter than in summer due to ice coverage. This can explain differences in the seasonal trends between ICES and BSIOM data. For example, ICES observational data show a much stronger decrease in surface salinity than the model data in SD 28. This might be partly related to a lack of measurements in the Gulf of Riga at the beginning of the time period. Fewer measurements in winter may also be the reason for the stronger haline stratification shown in the model compared to the observational data in the Gulf of Finland. When the Gulf of Finland is covered with ice in winter, the water below is protected from interactions with the atmosphere, which could cause stronger stratification of the water column. In addition, the accuracy of the measured values might not be consistent over the time period, as different methods were used (CTD and bottle measurements).

Various processes in the Baltic Sea itself, but also influences from its surrounding and the atmosphere have different effects on changes in the hydrography. We were able to explain some of the variations through atmospheric influences and the impact of river runoff. However, there are still many open questions that are worth further investigation in the future. For example, what hydrographic variations can be observed on larger timescales than presented here? In this context, Börgel et al. (2018) already indicate that the Atlantic Multidecadal Oscillation can play an important role and have an impact on salinity in the Baltic Sea, although this should be investigated in more detail.

Appendix A. Time series of temperature, salinity and oxygen

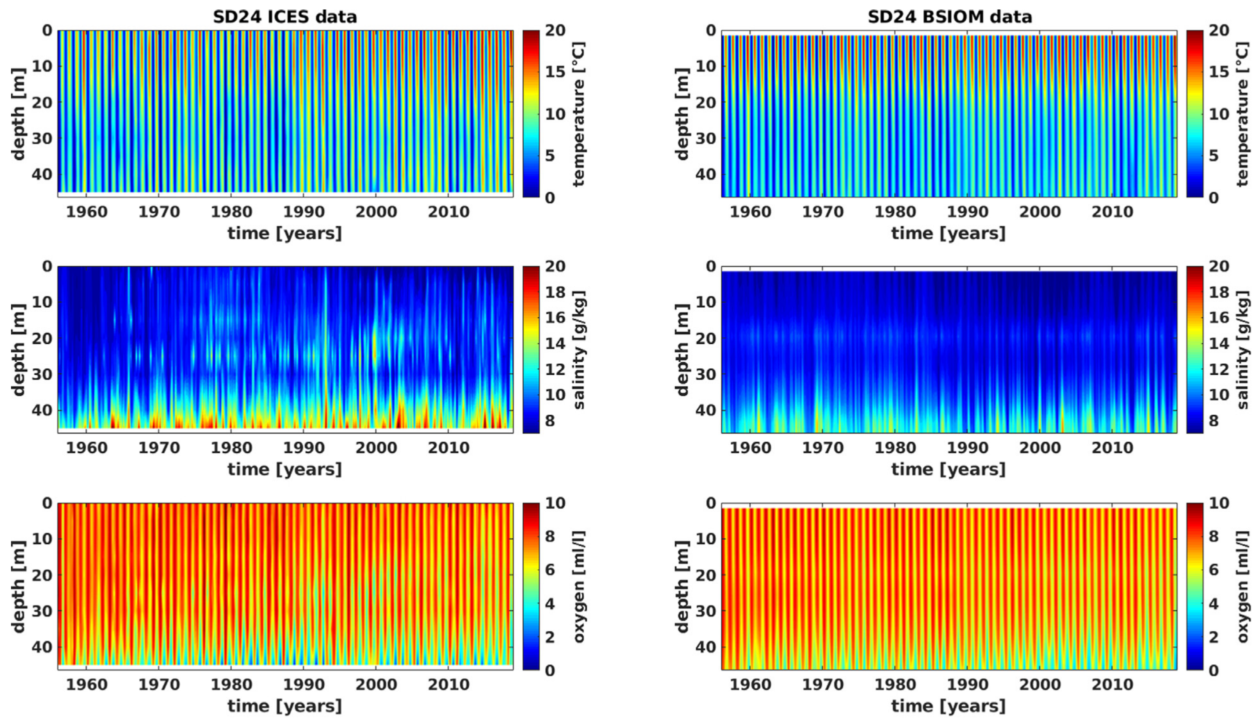

Figure A1 Time series of temperature, salinity and oxygen profiles based on monthly means of ICES observational data (left panels) and BSIOM model output (right panels) of SD 24 (Arkona Basin) for the period 1956—2018. The monthly mean data are filtered with a 3-month moving average.

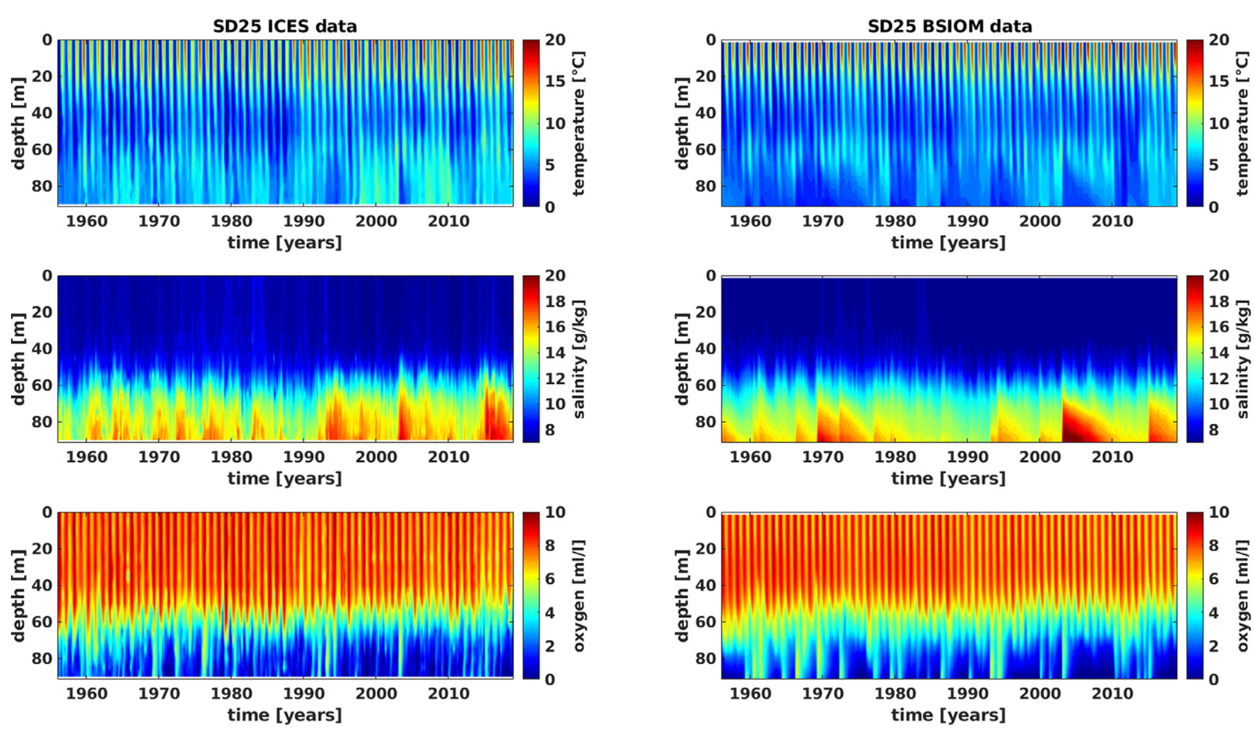

Figure A2 Time series of temperature, salinity and oxygen profiles based on monthly means of ICES observational data (left panels) and BSIOM model output (right panels) of SD 25 (Bornholm Basin) for the period 1956—2018. The monthly mean data are filtered with a 3-month moving average.

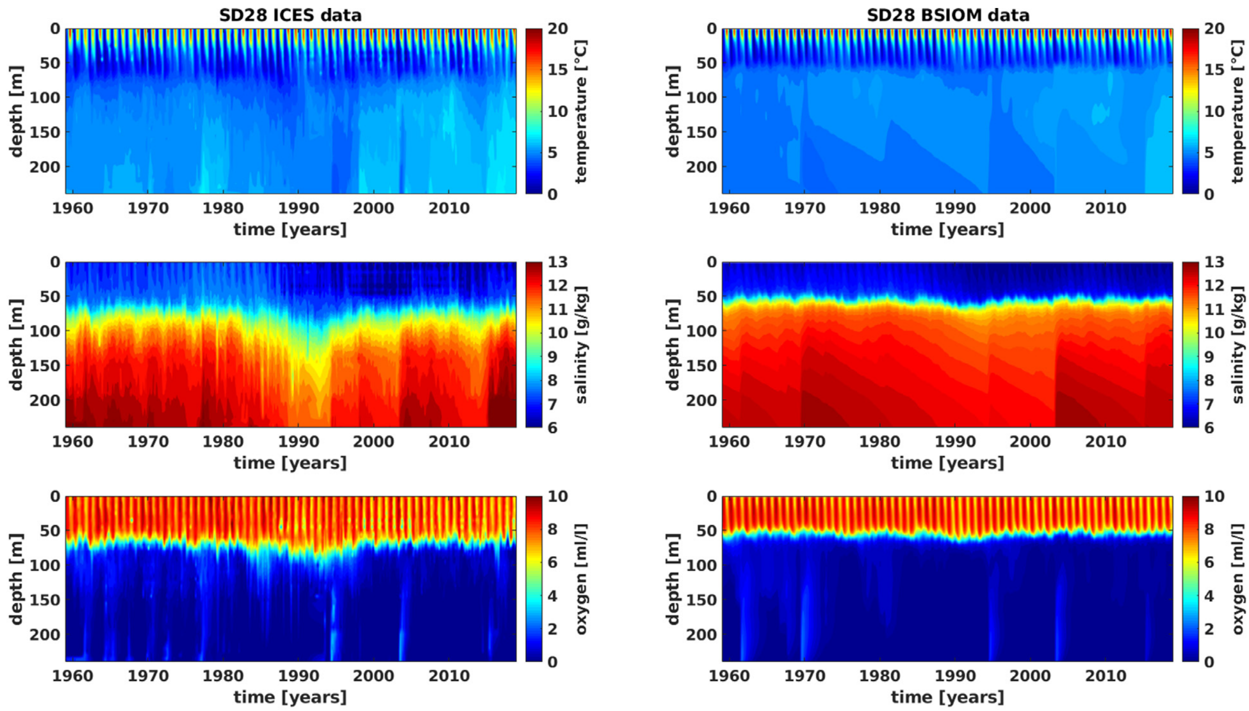

Figure A3 Time series of temperature, salinity and oxygen profiles based on monthly means of ICES observational data (left panels) and BSIOM model output (right panels) of SD 28 (Eastern Gotland Basin) for the period 1959—2018. The monthly mean data are filtered with a 3-month moving average.

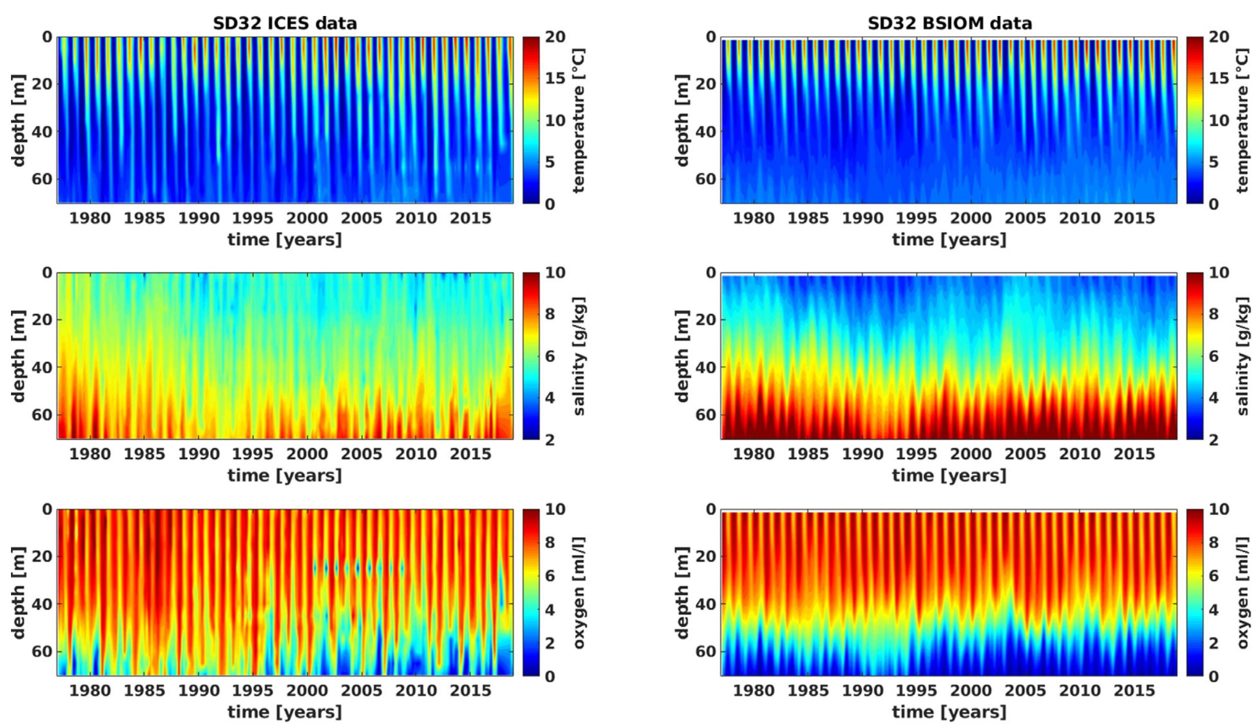

Figure A4 Time series of temperature, salinity and oxygen profiles based on monthly means of ICES observational data (left panels) and BSIOM model output (right panels) of SD 32 (Gulf of Finland) for the period 1977—2018. The monthly mean data are filtered with a 3-month moving average.

Appendix B. Correlations with the NAO index

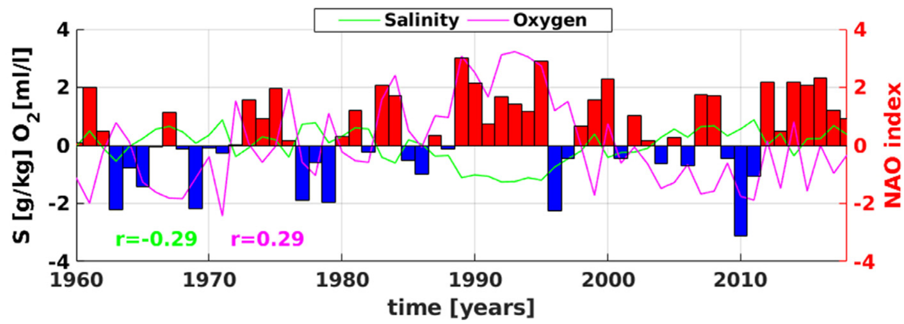

Figure B1 Winter (DJF) NAO index (bars) for the period 1959—2018 and DJF-mean salinity (green) and oxygen (magenta) in the area of the halocline based on ICES data for SD 28 (eastern Gotland Basin). In addition, the correlation coefficients between the NAO index and the salinity and oxygen time series are given. They are significant at the 5% level.

Table B1 Correlation coefficients between winter (DJF) NAO index and hydrographic parameters at the surface based on ICES and BSIOM data and atmospheric parameters based on ERA5 data. All-time series are averaged over DJF. * indicate correlations that are not statistically significant (5% level).

		SD 24	SD 25	SD 28	SD 32
Surface temperature	ICES	0.53	0.55	0.41	0.27*
	BSIOM	0.59	0.53	0.52	0.19*
Surface salinity	ICES	0.36	0.31	−0.23*	−0.13*
	BSIOM	0.41	0.2*	0.03*	−0.21*
Surface oxygen	ICES	−0.44	−0.44	0.29	−0.02*
	BSIOM	−0.61	−0.55	−0.53	−0.03*
2 m air temperature	ICES	0.71	0.70	0.69	0.69
Zonal wind speed	BSIOM	0.73	0.73	0.69	0.72
Precipitation	ERA5	0.28	0.16*	0.28	0.53

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