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Salinity dynamics of the Baltic Sea

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Abstract. In the Baltic Sea, salinity and its large variability, both horizontal and vertical, are key physical factors in determining the overall stratification conditions. In addition to that, salinity and its changes also have large effects on various ecosystem processes. Several factors determine the observed two-layer vertical structure of salinity. Due to the excess of river runoff to the sea, there is a continuous outflow of water masses in the surface layer with a compensating inflow to the Baltic in the lower layer. Also, the net precipitation plays a role in the water balance and consequently in the salinity dynamics. The salinity conditions in the sea are also coupled with changes in the meteorological conditions. The ecosystem is adapted to the current salinity level: a change in the salinity balance would lead to ecological stress for flora and fauna, as well as related negative effects on possibilities to carry on sustainable development of the ecosystem. The Baltic Sea salinity regime has been studied for more than 100 years. In spite of that, there are still gaps in our knowledge of the changes in salinity in space and time. An important part of our understanding of salinity is its long-term changes. However, the available scenarios for the future development of salinity are still uncertain. We still need more studies on various factors related to the salinity dynamics. Among others, more knowledge is needed, e.g., from meteorological patterns at various space scales and timescales as well as mesoscale variability in precipitation. Also, updated information on river runoff and inflows of saline water is needed to close the water budget. We still do not understand the water mass exchange accurately enough between North Sea and Baltic Sea and within its sub-basins. Scientific investigations of the complicated vertical mixing processes are additionally required. This paper is a continuation and update of the BACC (Baltic Assessment of Climate Change for the Baltic Sea Region) II book, which was published in 2015, including information from articles issued until 2012. After that, there have been many new publications on the salinity dynamics, not least because of the major Baltic inflow (MBI) which took place in December 2014. Several key topics have been investigated, including the coupling of long-term variations of climate with the observed salinity changes. Here the focus is on observing and indicating the role of climate change for salinity dynamics. New results on MBI dynamics and related water mass interchange between the Baltic Sea and the North Sea have been published. Those studies also included results from the MBI-related meteorological conditions, variability in salinity, and exchange of water masses between various scales. All these processes are in turn coupled with changes in the Baltic Sea circulation dynamics.

1 Introduction

The Baltic Sea salinity is not only a physical variable, but it also describes in an integrated way the simultaneous effects of the energy and water cycles in the sea; some of these features are typical just for the Baltic Sea, such as the low mean level of salinity and its pronounced variability. Several factors determine the observed structure of salinity. Due to the excess of river runoff to the sea, there is a continuous outflow of water masses in the surface layer. A compensating inflow to the Baltic Sea takes place from the Kattegat through the Danish Straits in the lower layer, strongly governed by the local atmospheric conditions. Also, the net precipitation over the sea plays a role in the water balance and consequently in the salinity dynamics. An essential role in salinity dynamics is played by the barotropic water exchange, which comprises irregular major Baltic inflows (MBIs; Matthäus and Franck, 1992) and large volume changes (LVCs; Lehmann et al., 2017), with MBIs as a subset of LVCs; see Sect. 4.1. These inflows have a significant impact on the modification of the observed patterns of stratification and oxygen conditions.

The Baltic Sea salinity regime has been studied for more than 100 years. Despite this long research history, there are still gaps in our knowledge of salinity changes in both space and time. Due to that, the available scenarios for the future are still uncertain. The projections indicate that precipitation will increase during the forthcoming decades. Hence, the ensemble mean of available scenarios shows a decrease in salinity by about 0.6 $\mathrm{g\,kg^{-1}}$ until 2100. The global rise of sea level has not been taken into account in these assumptions for the future (Saraiva et al., 2019). Due to the uncertainties in water balance estimates, there are inaccuracies in the climatic model scenarios: whether the Baltic Sea salinity will decrease or increase is still an open question. The Baltic Sea ecosystem is adapted to the current salinity level: a change in the salinity balance would lead to ecological stress for flora and fauna as well as related negative effects on possibilities to carry on sustainable development of the ecosystem (e.g., Vuorinen et al., 2015).

BACC II book (BACC II Author Team, 2015; Elken et al., 2015) includes a review of salinity dynamics based on publications until 2012. After that, the Baltic Earth community in particular has encouraged scientists to publish new results on that issue. In December 2014, a major Baltic inflow took place, and afterwards several papers were devoted to studying various aspects of such inflow events (see Mohrholz et al., 2015; Gräwe et al., 2015; Rak, 2016). Those studies revealed new results on multiple factors not only concerning MBIs, such as the link between long-term (decadal-scale) variability in climatic conditions with the salinity development in the Baltic Sea, MBIs and related barotropic exchange of mass and meteorological forcing conditions, variations in salinity and fluxes on various scales (observation and attribution to changes in climate), salt budget changes and the related variations in the Baltic Sea circulation, and induced changes in oxygen conditions.

This paper is organized as follows. Firstly, we summarize the knowledge which has been collected and summarized in BACC I (BACC I Author Team, 2008) and BACC II (BACC II Author Team, 2015) books and, e.g., in Leppäranta and Myrberg (2009) and Omstedt et al. (2014). Additionally, we assess recent publications and knowledge following the BACC process after 2012. This part starts with describing the atmospheric forcing which is driving the salinity dynamics, followed by a detailed update of the knowledge of salinity dynamics. Further on, we study new features of salinity dynamics on a regional scale concerning the sub-basins surrounding the Baltic Proper (Fig. 1). The various sub-basins respond differently to the changing atmospheric conditions. So, we highlight observed similarities and differences. Further, we summarize the climate change impact on salinity dynamics. Following that, oxygen conditions are analyzed in the central deep areas, being directly related to the dynamics of salinity. Thus, an improved understanding of the salinity dynamics will also deepen our knowledge of the processes concerning oxygen. Additionally, the salinity dynamics are also related to the environmental conditions of the marine ecosystem, like fisheries, in the Baltic Sea, which is discussed, too. The paper ends by discussing existing knowledge gaps, giving key messages for our present understanding of salinity dynamics, and suggesting necessary further work.

2 Salinity dynamics of different space scales and timescales – knowledge from BACC I and BACC II

Salinity dynamics have been discussed in both BACC books (BACC I Author team, 2008; BACC II Author Team, 2015) and, e.g., in Leppäranta and Myrberg (2009) and Omstedt et al. (2014). We will summarize earlier findings on salinity dynamics here to set up the basis of our current understanding.

- There was a decreasing trend of the mean salinity of the Baltic Sea both in the early 1900s and later during the century (1980s and 1990s); the latter is coupled with a complete lack of MBIs during 1983–1993. During those periods, freshwater inflows were larger than on average and zonal winds were stronger than normal, showing a very long-term natural variability in the highly dynamic system. During the stagnation periods with lower than normal salinities, the lack of inflows reaching the deep basins led to the situation in which the ventilation in the Gotland Basin was weak below the halocline. As a consequence of that, hypoxic bottom areas formed. However, towards the end of the period without inflows, the hypoxic area was shrinking because of the deepen-

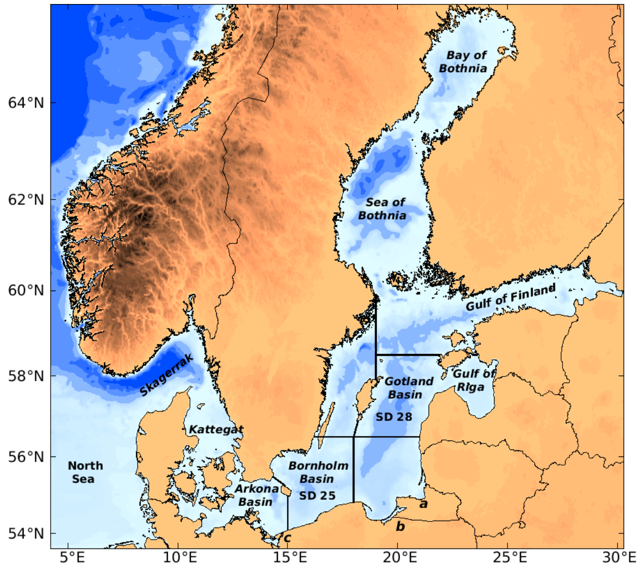

Figure 1. Map of the Baltic Sea and its sub-basins. The Baltic Proper comprises the sub-basins Arkona, Bornholm, and Gotland Basin. The Gulf of Bothnia comprises the Bothnian Sea and the Bay of Bothnia. Panels **(a)**–**(c)** denote the Curonian, Vistula, and Szczecin lagoons.

ing and weakening of the halocline. For example, in the Gulf of Finland, the halocline completely disappeared and the bottom oxygen conditions improved. However, despite the abrupt changes in deepwater salinity, there was no clear trend for the vertical mean salinity average of the entire Baltic Sea basin if we consider the entire 20th century.

- During the last 2–3 decades, the surface layer salinity was slightly lower than average and presumed to be driven by higher accumulated river runoff.

- MBIs, usually of barotropic origin, occur in favorable meteorological conditions, such as in winter and springtime. For an MBI to happen, there should firstly be winds from the east lasting for about 20 d, and after such a period, winds should blow from the west for several weeks. The back-to-back occurrence of these two wind events is not very common in the Baltic Sea, which keeps the natural frequency of MBIs relatively low.

- Later, after 1996, a different type of inflow was observed. Such events are baroclinically driven and take place during the summer period. In the same way as for barotropic events, such inflows transport water with higher salinity and temperature to the Baltic deeper layers. But, as the inflowing water volume of higher salinity is small compared to MBIs, the water stratifies in the halocline and is not able to substitute the bottom water. Summer inflows inject more highly saline water with higher temperatures and low oxygen content into the halocline. Most probably, such events have occurred before but could not be observed due to shortcomings in the observational strategy.

3 Atmospheric forcing driving the salinity dynamics of the Baltic Sea

The large-scale atmospheric circulation controls the local weather conditions over the Baltic Sea area, which in turn drives the circulation in the Baltic Sea and the distribution of temperature, salinity, and oxygen, which are relevant for biological production. Different weather regimes impact the trophic structure and the marine food webs (Lehmann et al., 2002; Hinrichsen et al., 2007b).

The speed and position of the Atlantic storm track or the polar jet stream are the most prominent features that influence the variability of the atmospheric conditions in the Baltic Sea region. The influence of this storm track could be described on various space scales and timescales. The mean salinity of the Baltic Sea is controlled by long-term variations such as river runoff as well as dry and wet periods. At the same time, salinity variations on smaller scales are driven by shorter-term events like barotropic exchange flows. Starting from the largest, which is the continental or hemispheric scale, teleconnection patterns are commonly used to describe the atmospheric circulation variability. The best-known of them is the North Atlantic Oscillation (NAO), which is the first mode of principal component analysis of the sea level pressure (SLP) field over the North Atlantic–European sector (Hurrel, 1995). The east Atlantic (EA) pattern (Wallace and Gutzler, 1981) and the Scandinavian pattern (SCA), also termed the Eurasian or blocking pattern, are described by the second and third mode, respectively (Hurrel and Deser, 2009). All these modes are better expressed in winter than in other seasons.

The NAO index or similar local indices (e.g., BSI – Baltic Sea index; Lehmann et al., 2002), which describe the strength of the zonal atmospheric circulation, are often related to the intermittent water exchange between the North Sea and Baltic Sea through the Danish Straits. The popularity of the NAO resulted from its relatively close connection with the decadal variability of the seasonal circulation in the years 1960–1990 when the NAO index increased and the correlation between the climatological variables in northern Europe (including the Baltic Sea surface elevation) was very high (Pinto and Raible, 2012; Feser et al., 2015; Lehmann et al., 2017). But the link is nonstationary, and therefore this simple approximation does not work for all periods (Cassou et al., 2004; Matulla et al., 2008; Lehmann et al., 2017). The analysis of winter SLP data highlighted considerable changes in intensification and location of storm tracks, parallel with the eastward shift of the NAO centers of action (Cassou et al., 2004; Lehmann et al., 2011). At the same time, a seasonal shift of extreme wind events from autumn to winter and early spring was found in the Baltic area.

The strength of windstorms is undoubtedly crucial for the salinity dynamics of the Baltic Sea. Zubiate et al. (2016) characterized the variability of wind speed and distribution as a function of the NAO and the current states of the secondary (EA) and tertiary (SCA) patterns of the SLP variability over Europe. A strong correlation at monthly timescales has been found between the NAO positive phase and wind speed in northern Europe. But this effect combines with different other patterns that vary with the sub-region. Over the Danish Straits, strong winds are associated with the combination of the NAO^{+}, EA^{-}, and SCA^{-} phase, while over Scandinavia, the NAO^{+} combined with EA^{+} initiates more storms. The temporal clustering of windstorms, also an essential player in wind climatology, has different large-scale drivers dominating over the Danish Straits. There is a triple point of NAO, SCA, and the polar index (POL), with POL dominating in the northern flank and the SCA over the Baltic Sea's southern side (Waltz et al., 2018). All this indicates that the Baltic Sea region is not homogeneous from the viewpoint of large-scale atmospheric variability. Thus, it is also essential to investigate forcing patterns at smaller scales.

The analysis of the synoptic-scale atmospheric circulation is based on classifying meteorological fields with various methods or tracking cyclones and anticyclones, mapping, and counting them (Barry and Carleton, 2013). Both kinds of approaches are applied to characterize the atmospheric conditions before, during, and after the events of large barotropic inflows or large volume changes (LVCs; Lehmann et al., 2017). From earlier studies (e.g., Schinke and Matthäus, 1998), it could be deduced that the synoptic-scale atmospheric forcing, which is vital during inflow events, could be described and interpreted by the usage of automated weather types. Two different synoptic classifications have been applied (Lehmann and Post, 2015; Post and Lehmann, 2016). During different phases of the inflow event, the number of certain classes (directions of synoptic-scale airflow) increases or decreases compared to the average frequency of classes. About 60 d before the maximum inflow, which corresponds to the maximum sea surface elevation at Landsort, the frequency of eastern and southeastern classes increases for about 30 d. This confirms the results of Matthäus and Schinke (1994) about the pre-inflow period with prevailing easterly winds and less precipitation to enhance the outflow of Baltic Sea water, lowering the mean sea level. At the same time, the wedge-shaped salinity front in the Danish Straits becomes more tilted by the movement of more highly saline bottom water in the direction of the sill. An immediate period of very strong westerly winds starting about 30 d before the maximum inflow forces effective LVCs and MBIs (see Sect. 4.1). Atmospheric forcing is more strongly associated with LVCs than MBIs, while it directly controls the sea level and indirectly the amount of salt of the inflowing water mass. Thus, MBIs are considered a subset of LVCs.

Barotropic inflow events like LVCs and MBIs are driven by a sequence or accumulation of atmospheric forcing (Lehmann et al., 2017). During barotropic inflow events, which last about 40 d, five to six temporally clustered deep cyclones move along characteristic pathways or storm tracks.

One possible reason for less frequent MBIs in the 1980s might be the increased atmospheric zonal circulation associated with increased precipitation and runoff at the expense of pre-inflow easterly wind periods (Schinke and Matthäus, 1998; Lehmann et al., 2002, 2011; Meier and Kauker, 2003). Soomere et al. (2015) proposed an alternative explanation. The meridional airflow direction over the southern Baltic Sea changed around 1987 to northwestern wind events at the expense of wind directions necessary for MBIs to occur.

4 Update of the knowledge of salinity dynamics since 2012

4.1 Large volume changes and major Baltic inflows

Despite a long history of Baltic Sea studies, still today, an important objective for investigations is the dynamics of water exchange between the North Sea and the Baltic Sea. A critical study object is the transition area between the two seas: the Danish Straits.

Furthermore, pronounced changes in the salinity in the Gotland Deep, situated in the central Baltic, are strongly dependent on major saltwater inflows, MBIs. These events, which are a subset of LVCs, represent a specific type of barotropically driven inflows. Their formation depends on specific favorable meteorological circulation patterns (e.g., Matthäus et al., 2008; Leppäranta and Myrberg, 2009; Lehmann and Post, 2015) and spatiotemporal grouping of deep cyclones (Lehmann et al., 2017).

Recently, a number of investigations have been carried out on the role of meteorological forcing and its impact on the hydrographic conditions in the Danish Straits, as well as the total freshwater supply to the Baltic Sea before the occurrence of highly saline barotropically driven inflows. Höflich and Lehmann (2018) proposed a mechanistic explanation including the salinity in the Danish Straits as well as the time variability of meteorological forcing in connection with an inflow taking place. Freshwater supply played only a modulating role; i.e., it does not lead to a change in frequency or intensity of the events. However, it had an adjusting role in observed transports of saline water to the Baltic Sea.

The third-largest MBI ever observed took place in December 2014, generating interest in studying the saline inflows further (e.g., Mohrholz et al., 2015; Gräwe et al., 2015; Rak, 2016; Neumann et al., 2017; Liblik et al., 2017). Mohrholz (2018) reanalyzed the time series of major inflows. He used long-term data on sea levels, river runoff, and observed salinity in the Belt Sea and the Sound. As a result, an ongoing time series (revised list of MBIs) of barotropically driven inflows was formed from about 1890 until today. The new time series by Mohrholz (2018) were compared with those composed by Fischer and Matthäus (1996), which could be considered a traditional list of MBIs. There were apparent differences between the two series from the 1980s onwards. There were many reasons behind the observed deviations. Not many accurate data during the 1976–1991 period were available. After that time, the methods to observe the inflows were changed, which caused a bias in the statistics. Moreover, the locations where the measurements took place were changed (Mohrholz, 2018).

There is a clear difference in the revised time series of the MBIs compared with the earlier, traditional ones. Namely, according to Mohrholz (2018), there is no clear trend in the frequency and intensity of the MBIs on the decadal timescale. In the traditional assumption, climate change would have impacted MBIs as a decreasing trend in their frequency. On the other hand, variability was found in the frequency of the inflows with a timescale of about 30 years (Mohrholz, 2018; Radtke et al., 2020).

This decadal variability was also found in surface and bottom salinities, river runoff, and salt transport across the Darss Sill (Radtke et al., 2020). It also turned out that LVCs and MBIs are not the only events which transport salt into the Baltic Sea. There are also smaller inflows of barotropic origin. These occur during all seasons, having a low variability between the years. Such inflows bring about 30 % of the entire salt transport to the Baltic Sea. Normally, the salinity of the inflowing water is not high enough to substitute the bottom water of the deep basins. Thus, this water will be stratified in the corresponding density layer within or below the halocline (e.g., Reissmann et al., 2009; Naumann et al., 2018). This variability of the saline water inflows in time does not explain the worsening of oxygen conditions in the Gotland Basin (anoxic bottoms) and the observed prolonged periods of stagnation (Mohrholz, 2018). Large barotropic inflows and the associated dense bottom currents form one branch of the Baltic Sea overturning circulation and deepwater ventilation. Holtermann et al. (2017) investigated the dynamics of the deep waters and vertical mixing in the central part of the Baltic Sea while major Baltic inflows took place, thus providing new information on dense bottom gravity currents on their way to the deep Gotland Basin and associated turbulent mixing. They showed that the large-scale inflow event could be separated into three phases extending over 5 months. During Phase I, near-bottom intrusions of only moderate oxic waters could be detected, most likely by displaced saline deep water from the Bornholm Basin. The main inflow pulse arrived in the deep Gotland Basin in Phase II, leading to an instantaneous expansion of the oxic deepwater pool. This was followed by Phase III, a longer period of oxic intrusions accumulating in almost the same amount of oxic waters as in Phase II. Furthermore, mixing was mostly happening in a thin bottom gravity current propagating down the slope, but at the same time the interior region remained nonturbulent.

Liblik et al. (2018) studied the impact of the December 2014 MBI downstream from the eastern Gotland Basin to the Gulf of Finland. Although the deep Gotland Basin was well ventilated, oxygen conditions in the area north of the Gotland Deep did not improve but rather worsened in the northern Baltic Proper and Gulf of Finland. A further study by Stramska and Aniskiewicz (2019) showed that remote sensing altimetry could be a complementary source of information about barotropic inflow events.

4.2 The cold intermediate layer

A Baltic-specific physical feature is the so-called cold intermediate layer (hereafter denoted as CIL), which is formed annually. The CIL appears as a temperature minimum between the thermocline and the permanent halocline from spring to autumn. Vertical convection due to cooling of the atmosphere and wind mixing erode the seasonal thermocline during autumn and winter (Leppäranta and Myrberg, 2009; Stepanova, 2017). During this process, the water masses of the fresher upper layer and the sub-thermocline saltier layer are mixed. As a result, the seasonal salinity maximum in the surface layer occurs in winter (Reissmann et al., 2009). This mixing process extends down to the upper boundary of the permanent halocline (Figs. 2 and 3). In areas where the permanent halocline does not exist, such as the Gulf of Riga and the Gulf of Bothnia (Fig. 1), mixing leads to a complete turnover of the entire water column almost every winter (Raateoja, 2013; Raudsepp, 2001). With the formation of the seasonal thermocline, the CIL is formed as a separated layer between the thermocline and the permanent halocline. Its thickness has been estimated to be 20–50 m (Liblik and Lips, 2017; Stepanova, 2017). Despite the rapid warming of the thermal mixed layer, the temperature of the CIL only slowly increases during summer and autumn (Hinrichsen et al., 2007a; Liblik and Lips, 2011). However, the CIL can be traced in the water column until the next winter (Liblik et al., 2013; Stepanova, 2017), when a new CIL is formed. The water temperature in the CIL correlates with the severity of the previous winter (Hinrichsen et al., 2007a; Liblik and Lips, 2011). After the formation of the thermocline in spring, CIL temperature is often lower than the temperature of maximum density (Tmd), most probably due to lateral advection of slightly more highly saline, dense water. This buoyancy flux is stronger than the destabilizing effect caused by the warming of the water, when $T <$ Tmd (Chubarenko et al., 2017a; Eilola and Stigebrandt, 1998).

According to Chubarenko and Stepanova (2018), colder and slightly saltier water, which has its origin from the upper layer of the Bornholm Basin, advects to the east and forms the core of the CIL in the Baltic Proper. Wind-driven pycnocline variations, including coastal upwelling and downwelling events, considerably alter the depth and thickness of the CIL (Liblik and Lips, 2017). No remarkable changes

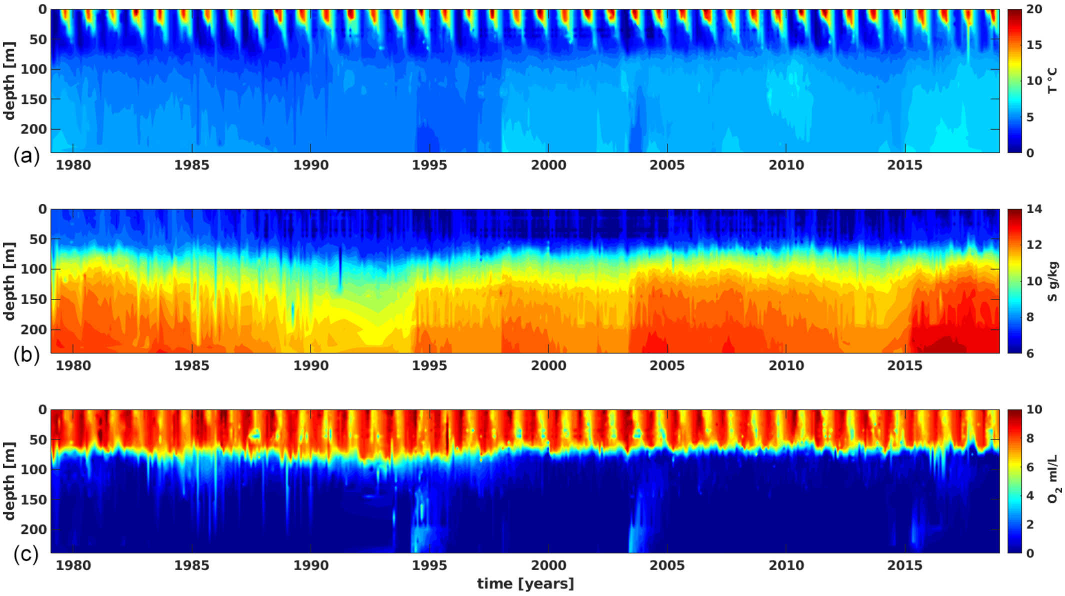

Figure 2. Observed temperature **(a)**, salinity **(b)**, and oxygen **(c)** data as a function of depth and time. Subdivision 28 (SD 28, eastern Gotland Basin) for the period 1979–2018. Data from the ICES Marine Data Centre (https://www.ices.dk/Pages/default.aspx, last access: 12 August 2019).

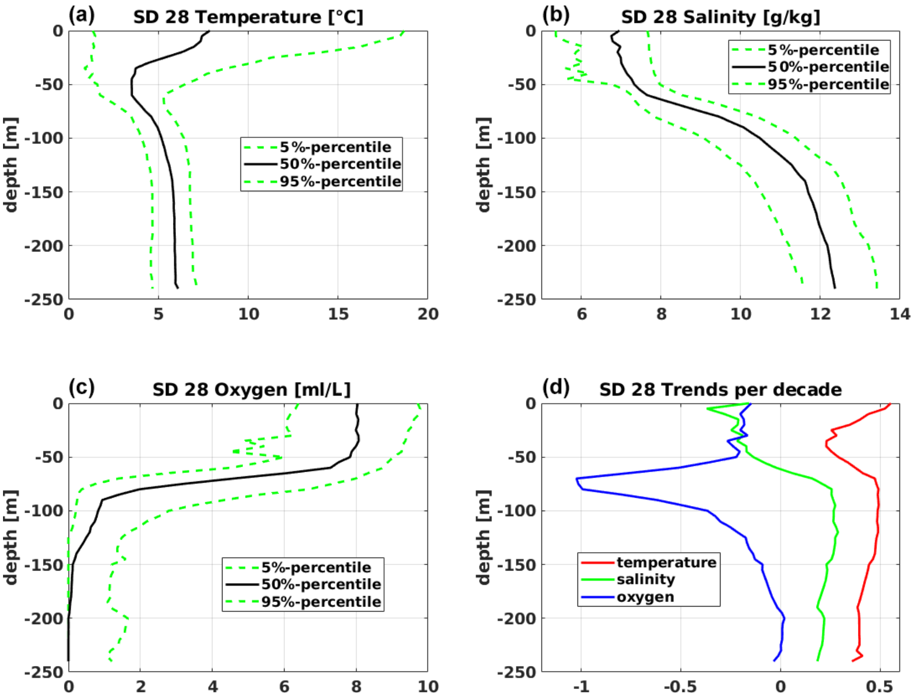

Figure 3. Percentiles (5 %, 50 %, and 95 %) of temperature **(a)**, salinity **(b)**, and oxygen **(c)** profiles for Subdivision 28 (SD 28, eastern Gotland Basin) for the period 1979–2018. Trends per decade of temperature, salinity, and oxygen based on SD 28 temperature, salinity, and oxygen profiles for the period 1979–2018 **(d)**.

occurred in temperature and salinity in the CIL from 1982 to 2016 (Liblik and Lips, 2019).

5 New knowledge of regional salinity dynamics

5.1 Salinity dynamics of the eastern Gotland Basin and the Gulf of Riga

The eastern Gotland Basin as part of the Baltic Proper (Fig. 1) is the most prominent region to investigate the impact of barotropic inflows and long-term salinity changes in the Baltic Sea. The salinity dynamics of the eastern Gotland Basin are also affecting the different sub-basins and lagoons surrounding it. The salinity dynamics there represent the development of salinity and stratification with sufficient accuracy in the entire Baltic Proper. Changes in the mean salinity calculated from Gotland Deep's position are only about 2 % different from the calculation based on all sub-basins (Winsor et al., 2001, 2003; Elken et al., 2015). However, only about 12 % of the total area of the Baltic Sea has a depth of more than 100 m and 2.7 % more than 150 m (Leppäranta and Myrberg, 2009). Observed surface salinity of the eastern Gotland Basin (Figs. 2 and 4) reveals a low-salinity period starting in the 1980s (Elken et al., 2015; Vuorinen et al., 2015; Liblik and Lips, 2019) and lasting until 2002. After the MBI in 2003, the surface salinity slightly increased and fluctuated until 2018, but it remains relatively low ($< 6.5\,\mathrm{g\,kg^{-1}}$; Fig. 4). The deepwater salinity decreased from the late 1970s until 1993 and then increased until 2018 (Fig. 2). Major saltwater inflows after 1994 can be traced by the abrupt salinity increase in the layers below the halocline. There are also smaller barotropic inflows (Mohrholz, 2018), keeping the salinity below the halocline on a high level (Fig. 2). A negative salinity trend of about 0.1–0.2 $\mathrm{g\,kg^{-1}}$ per decade can be detected at the surface. The surface temperature increases by about 0.4–0.6 °C per decade, whereas surface oxygen decreases by 0.1–0.2 $\mathrm{mL\,L^{-1}}$ per decade (Fig. 3). Generally, the temperature trend at the surface of the Baltic Sea follows the trend in air temperature. Increasing temperatures reduce the solubility of oxygen and at the same time enhance oxygen depletion rates. Maximum negative trends in oxygen up to 1 $\mathrm{mL\,L^{-1}}$ per decade can be found in the area of the halocline (Bornholm and Gotland Basin, Fig. 3). The surface salinity trend is decreasing, whereas salinity below the halocline is increasing (0.2–0.25 $\mathrm{g\,kg^{-1}}$ per decade), leading to enhanced stratification between the surface and deep layer. However, the frequency of barotropic and major Baltic inflows did not increase. The decreasing trend in surface salinity might be due to increased runoff and net precipitation (Liblik and Lips, 2019). The volume-averaged salinity also shows a drop until 1992, and with the MBI in 1993, a gentle increase occurred (Figs. 4 and 5).

The Gulf of Riga is a seasonally stratified, semi-enclosed basin in the eastern Baltic Sea (Fig. 1), where the water column is fully mixed every autumn–winter. The gulf has two shallow connections with the Baltic Proper: the Irbe Strait (sill depth 25 m) and the Väinameri Sea area (sill depth 5 m). The water budget in the gulf is determined by the water mass transport through these two openings (Laanearu et al., 2000; Lilover et al., 1998; Otsmann et al., 2001) and river discharge, which is concentrated in the southern part of the gulf. Due to the shallow straits, the sub-halocline salty water does not intrude from the Baltic Proper to the gulf, and no permanent halocline exists there. Stratification in early spring is dominated by haline stratification (Stipa et al., 1999), especially close to the freshwater sources, but later in spring and summer, thermal stratification becomes more important in stabilizing the water column (Berzinsh, 1995; Liblik et al., 2017). Thus, the water column is stratified from spring to late autumn (Berzinsh, 1995), but the mean salinity difference between the upper and deep layers is only 0.7–1.0 $\mathrm{g\,kg^{-1}}$ (Raudsepp, 2001; Skudra and Lips, 2017). There is quite a high correlation between river runoff in spring and mean salinity in the upper mixed layer in August (Skudra and Lips, 2017). Bottom layer salinity in the gulf is well correlated with the near-bottom salinity in the Irbe Strait (Skudra and Lips, 2017). Long-term changes in the average salinity are characterized by an increase from the 1960s to the late 1970s and a consecutive decrease in the 1980s–1990s (Berzinsh, 1995). The latter trend of decreasing salinity in the gulf coincided with the corresponding changes in the Baltic Proper in the layer above the halocline during the stagnation period until the mid-1990s (Raudsepp, 2001; Figs. 2 and 4).

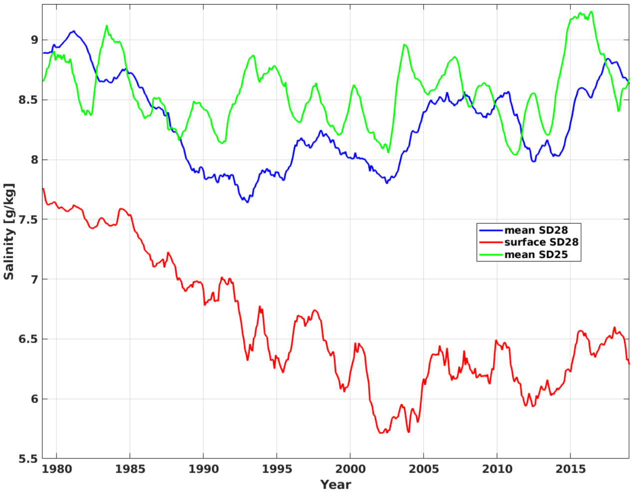

Figure 4. Mean salinity of Subdivision 28 (SD 28, eastern Gotland Basin) (blue) and surface salinity of SD 28 (red). For comparison, the mean salinity of SD 25 (Bornholm Basin) (green) is shown for the period 1979–2018. All series are 12-month running means.

Wind-driven processes modify the transport of saltier water from the Irbe Strait and the advection of riverine water (Liblik et al., 2017; Lips et al., 2016b, c; Soosaar et al., 2014, 2016). Most of the fresh water from the Daugava River is transported to the north along the eastern shore during the

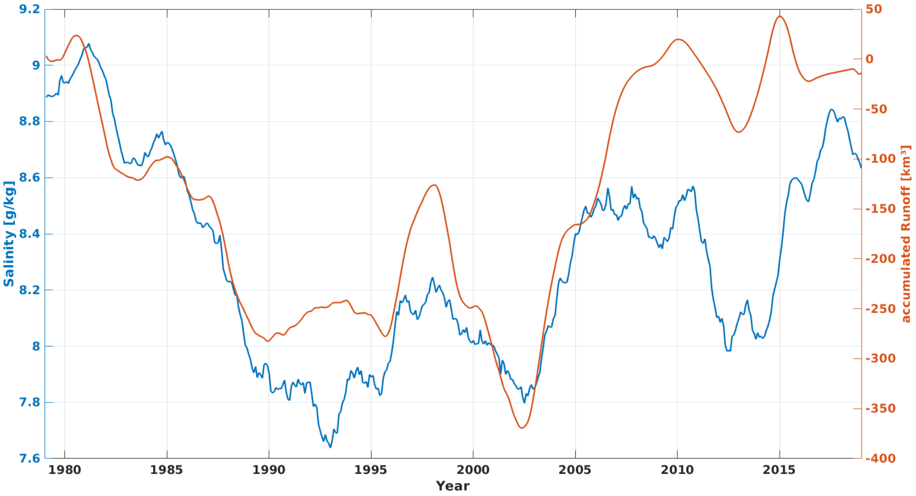

Figure 5. Volume-averaged salinity of Subdivision 28 (SD 28, eastern Gotland Basin) for the period 1979 to 2018 and accumulated anomalies of runoff to the Baltic Sea (inverted). The correlation coefficient is 0.75. All series are 12-month running means. Runoff data from http://helcom.fi/baltic-sea-trends/environment-fact-sheets (last access: 14 February 2022).

cold season (Lips et al., 2016b). An anticyclonic gyre in the southern part of the gulf (Soosaar et al., 2014) or the entire gulf (Lips et al., 2016b) could form in spring–summer under specific wind forcing. Modeling experiments have also indicated that cyclonic eddies could develop and transport the saltier water from the Irbe Strait towards the central gulf (Lips et al., 2016c). High-resolution measurements have shown an entering of the subsurface warmer, saltier, and oxygen-rich buoyant patches from the Irbe Strait into the gulf intermediate layer in summer. The exact shape, fate, and impact of these sub-mesoscale features are unknown, but they showed up as strong subsurface salinity maxima in the time series (Liblik et al., 2017).

Salinity dynamics of lagoons

Some of the largest European lagoons (e.g., Curonian Lagoon, Vistula Lagoon, Szczecin Lagoon) are situated in the Baltic Sea (Fig. 1). As the Baltic Sea can be considered a large estuary, the Gulf of Finland, the Gulf of Bothnia, and the Gulf of Riga can be described as estuaries of medium scale, and lagoons form the small-scale end. Common to all estuaries is the local circulation driven by the salinity difference inside and outside the estuary (Leppäranta and Myrberg, 2009). The salinity regime of lagoons is closely related to the water balance components, including river runoff, seawater inflows and intrusions, precipitation, and evaporation. All these water balance elements, as well as the air temperature, sea surface temperature, and sea level, are changing and can be expected to change in the future due to climate change in the Baltic Sea region. For instance, the warming trend of the mean surface water temperature in the southeastern lagoons of the Baltic Sea was 0.03 °C yr^{-1} in the period 1961–2008 and about 0.05 °C yr^{-1} after 1980 (Dailidiene et al., 2011; compare with Fig. 3). In the Curonian Lagoon and the Vistula Lagoon, the water level rose 18 cm between 1961 and 2008, corresponding to a rate of $\sim 4\,\mathrm{mm\,yr}^{-1}$ (Dailidiene et al., 2011). Furthermore, human activities such as river regulation and deepening port areas or inlets can directly affect the water balance and salinity dynamics.

The Curonian Lagoon, located in the southeastern part of the Baltic Sea (Fig. 1), is the largest coastal shallow lagoon in Europe. It has a narrow connection to the Baltic Sea in the north (Klaipeda Strait with a width of 300–600 m). The lagoon receives freshwater discharge varying between 14 and 33 $\mathrm{km}^3\,\mathrm{yr}^{-1}$ (Jakimavičius et al., 2018), with the dominant contribution from the Nemunas River. The total river runoff to the lagoon is on average about 22 $\mathrm{km}^3\,\mathrm{yr}^{-1}$, and it exhibits a strong seasonal pattern, peaking with snowmelt during the flood season in February–April (Jakimavičius et al., 2018).

The water in the Curonian Lagoon is theoretically exchanged in about 80 d. In the southern and central parts, which are directly influenced by river runoff, salinity is only up to 0.05 $\mathrm{g\,kg}^{-1}$. In the northern part, salinity fluctuates between 0 and 7.5 $\mathrm{g\,kg}^{-1}$. The inflow of saline water from the Baltic Sea depends on the meteorological conditions. Furthermore, due to dredging in the transition area to the Baltic Sea, the annual mean salinity is increasing. For example, winds blowing from the north and northeast may lead to an inflow of saltier waters into the lagoons. The Baltic Sea water can reach the central Curonian Lagoon even 40 km from the entrance during upwelling. Climate change projections reveal an increase in the Curonian Lagoon's salinity, linked to changes in water exchange through the Klaipėda Strait and the Nemunas runoff (Jakimavičius et al., 2018).

The Vistula Lagoon, the second-largest lagoon in the Baltic Sea (Fig. 1), has an average salinity of 3.5 $\mathrm{g\,kg}^{-1}$, and the salinity may vary from 0.5 $\mathrm{g\,kg}^{-1}$ in the southern part up to 6.5 $\mathrm{g\,kg^{-1}}$ at the Baltyisk Strait. The water balance of the Vistula Lagoon was estimated by Różyński et al. (2018): yearly, 17 $\mathrm{km^3}$ (80.2 %) of water enters the lagoon through the Baltyisk Strait. Riverine inflows amount to 3.62 $\mathrm{km^3}$ (17.1 %), atmospheric precipitation 0.5 $\mathrm{km^3}$ (2.4 %), evaporation 0.65 $\mathrm{km^3}$ (3.1 %), and groundwater inflows 0.07 $\mathrm{km^3}$ (0.3 %). While the Curonian Lagoon has maintained the same environmental conditions over ages, the Vistula Lagoon experienced considerable anthropogenic modification at the end of the 19th century, evolving from a freshwater coastal lake to an estuarine lagoon with predominant marine influence (Chubarenko et al., 2017b). There are plans for constructing a second inlet to the lagoon at the Polish side (Różyński et al., 2018) that could change the water balance of the lagoon in the future.

The Szczecin Lagoon (Fig. 1) is also one of the largest lagoons in Europe. The lagoon is shallow with an average depth of only 3.8 m. The salinity varies between 1 and 3 $\mathrm{g\,kg^{-1}}$, and the lagoon is connected to the Baltic Sea via three outlets (Friedland et al., 2019). The residence time of water in the Szczecin Lagoon is about 75 d.

The sea surface temperature in the Curonian Lagoon is projected to increase by 2–6 °C by the year 2100 (Jakimavičius et al., 2018). Water temperature and sea level rise could lead to an increase in salinity due to less restricted water exchange between the Baltic Sea and the lagoons. The average water level of the lagoons is usually higher than that of the Baltic Sea. In the future, the sea level of the Baltic Sea is projected to rise, resulting in a possible widening and deepening of connecting inlets. Thus, the water exchange between lagoons and the Baltic Proper will increase, leading to a decrease in the difference in sea level heights and an increase in salinity in the lagoons.

5.2 Salinity dynamics of the Gulf of Finland

The Gulf of Finland is an elongated sub-basin of the Baltic Sea located in the northeastern extremity of the sea (Fig. 1). The length of the gulf is about 400 km, and its width varies between 48 and 135 km (Myrberg, 1998). The mean depth of the gulf is 37 m, with the maximum depth being 123 m (in the Baltic Sea 459 m). The drainage area of 420 990 $\mathrm{km^2}$ is 20 % of the total drainage area of the entire Baltic Sea. The water budget in the gulf is mainly determined by unrestricted and continuous water exchange with the northern Baltic Proper in the west and river discharge, which is mainly concentrated in the eastern part, where the largest river of the entire Baltic Sea is located, namely the river Neva. The water column can be divided into three layers – the upper mixed layer, the cold intermediate layer, and the sub-halocline near-bottom layer separated by the seasonal thermocline and the quasi-permanent halocline (Alenius et al., 1998, 2003; Soomere et al., 2008). The seasonal thermocline vanishes on a yearly basis during autumn–winter. Strong wind events, reversing the estuarine circulation (Elken et al., 2003), can occasionally destroy the halocline for more than a month in large areas of the gulf in winter (Liblik et al., 2013). Surface salinity increases from about 1 $\mathrm{g\,kg^{-1}}$ in the easternmost part to 6 $\mathrm{g\,kg^{-1}}$ in the western part. On average, surface salinity is higher near the southern coast than the northern coast (Kikas and Lips, 2016; Liblik and Lips, 2017) due to the general cyclonic circulation scheme (Andrejev et al., 2004a, b). The westward-flowing current along the northern coast changes its location across the gulf mainly due to wind forcing (Kikas and Lips, 2016; Liblik and Lips, 2017; Lips et al., 2016a).

Wind-driven processes, such as the along-gulf advection, coupled upwelling and downwelling events, and vertical mixing, play an important role in the salinity dynamics. Westerly winds bring the saltier upper layer water to the gulf from the Baltic Proper (Lilover et al., 2016; Suhhova et al., 2018), weaken the stratification, and deepen the upper mixed layer (Liblik and Lips, 2017). Easterly winds have an opposite effect; these intensify the transport of fresher waters to the west (Elken et al., 2003; Liblik and Lips, 2012), make the mixed layer shallower, and strengthen the haline stratification (Liblik and Lips, 2017). The latter process can lead to the formation of the shallow haline stratification in winter (Liblik et al., 2013). Shallowing or deepening of the upper mixed layer due to the prevailing winds can be an important factor influencing the primary production and species dominance during the summer cyanobacteria blooms (Kanoshina et al., 2003).

Coupled upwelling and downwelling events bring denser water from the cold intermediate layer to the surface layer, where it mixes with the ambient upper layer water (Myrberg and Andrejev, 2003; Lips et al., 2009). Upwelling–downwelling events at the southern and northern coast have several distinctive characteristics. Less wind forcing is needed to generate upwelling along the southern coast than the northern coast (Kikas and Lips, 2016; Liblik and Lips, 2017). Stronger lateral salinity, temperature, and density gradients occur in the upper layer in the case of upwelling along the southern coast (Kikas and Lips, 2016; Liblik and Lips, 2017). Eastward advection in the surface layer and downwelling along the southern coast generated by westerly winds can form a thick upper mixed layer (> 45 m) in summer (Liblik and Lips, 2017). A positive trend in the upwelling occurrence along the northern coast was detected in 1990–2009 (Lehmann et al., 2012). However, no long-term trends were seen in the upwelling-favorable winds in 1982–2013 (Liblik and Lips, 2017).

In situ measurements and modeling experiments have been conducted to characterize sub-mesoscale processes and their impact on the development of stratification and vertical mixing in the gulf (Lips et al., 2016a; Väli et al., 2013; Vankevich et al., 2016).

The gulf is impacted by estuarine circulation reversals caused by westerly wind impulses (Elken et al., 2003), which considerably weaken the halocline and lower salinity in deep layers (Elken et al., 2003; Lilover et al., 2016; Stoicescu et al., 2019). In the case of long-lasting, strong westerly winds, circulation reversals can lead to the vanishing of the stratification in large areas of the gulf in winter (Liblik et al., 2013; Lips et al., 2017). Stratification collapse events have become more frequent since the 1990s (Elken et al., 2014). More frequent and stronger westerly winds during winters (Keevallik and Soomere, 2014) generate more reversals and likely cause a salinity minimum in the annual cycle of the deep layer (Lehtoranta et al., 2017; Maljutenko and Raudsepp, 2019). The reversals, together with upward salt flux created by convective and wind mixing, cause a maximum in the annual cycle of the upper layer salinity in the winter period. A salinity maximum or minimum usually occurs in the deep or surface layer in summer, when the seasonal thermocline restricts vertical mixing and westerly winds are not that dominant. Additionally, the seasonal maximum in river runoff during spring will lead to a surface salinity reduction (e.g., Eilola and Stigebrandt, 1998). Another minimum in the sea surface salinity might occur due to a lack of vertical mixing in the ice-covered areas in late winter (Merkouriadi and Leppäranta, 2014).

Multiyear changes in salinity in the deep layer depend on the occurrence of MBIs (Laine et al., 2007; Liblik et al., 2018; Liblik and Lips, 2011). If the water exchange with the North Sea was artificially limited in a numerical experiment, salinity would decrease in the deep layer of the gulf (Lessin et al., 2014). After the recent MBIs (Naumann et al., 2018), salinity peaked at 10.77 $\mathrm{g\,kg^{-1}}$ in the near-bottom layer of the central gulf (Liblik et al., 2018), which is the highest value since 1974 (Alenius et al., 1998). Former deep layer water from the northern Baltic Proper was pushed to the gulf 9 months after (Liblik et al., 2018) the MBI occurred in December 2014 (Mohrholz et al., 2015). The MBI water, which originates from the depths of 110–120 m in the eastern Gotland Basin (compare with Fig. 2), arrived in the gulf 14–15 months after the inflow (Liblik et al., 2018).

Decadal trends of salinity show vertically distinct changes. The surface salinity decrease since the early 1980s has been estimated to be in the range from 0.005 $\mathrm{g\,kg^{-1}}$ (Liblik and Lips, 2019) to 0.02 $\mathrm{g\,kg^{-1}\,yr^{-1}}$ (Almén et al., 2017). Long-term records close to the island of Utö revealed a sea surface salinity decrease from the early 1980s to mid-1990s (Laakso et al., 2018; compare with Figs. 2 and 4). However, the surface salinity increased by 0.5 $\mathrm{g\,kg^{-1}}$ during 1927–2012 in the northwestern part of the gulf (Merkouriadi and Leppäranta, 2014). The salinity trend in the deep layer of the central gulf has been estimated to be 0.04 $\mathrm{g\,kg^{-1}\,yr^{-1}}$ from 1982–2016 (Liblik and Lips, 2019).

5.3 Salinity dynamics of the Gulf of Bothnia

The mean depth of the Gulf of Bothnia is 55 m, and its surface area is 30 % of the entire Baltic Sea. The Gulf of Bothnia is connected to the northern Baltic Proper by sills and archipelagos. Its hydrography is quite different from other parts of the Baltic Sea (Fig. 1). The sill between the Åland Sea and Baltic Proper prevents the northward propagation of deepwater flow. It is assumed that the water masses in the Bothnian Sea are renewed mainly by inflowing surface water from the Baltic Proper (Marmefelt and Omstedt, 1993; Meier, 2007). The net water exchange through the Archipelago Sea is estimated to be low compared to the Åland Sea (Omstedt et al., 2004; Myrberg and Andrejev, 2006; Tuomi et al., 2018). In the Gulf of Bothnia, the salinity stratification is weak. The surface salinity in the Åland Sea is about 5.25–6.25 $\mathrm{g\,kg^{-1}}$, whereas at a depth of 200 m, salinity varies between 7 and 7.75 $\mathrm{g\,kg^{-1}}$. Deep salinity in the Åland Sea and the Bothnian Sea stems from the upper homohaline layer of the northern Baltic Proper. Additionally, a small fraction of more saline deep water flows in over sills. The inflow of saline water through the Åland Sea over the sills can cause a corresponding flow of fresher water out into the Gotland Basin. This strengthens the stratification in the Bothnian Sea (Leppäranta and Myrberg, 2009).

In the Bothnian Sea (Fig. 1), the surface salinity varies between 4.8 and 6.0 $\mathrm{g\,kg^{-1}}$, and in the lower layer at 150 m depth, the salinity is 6.4–7.2 $\mathrm{g\,kg^{-1}}$. In the Bay of Bothnia (Fig. 1), the salinity is between 2 and 3.8 $\mathrm{g\,kg^{-1}}$, and at 100 m depth near the bottom it varies between 4 and 4.5 $\mathrm{g\,kg^{-1}}$. The Gulf of Bothnia has many rivers, and near the river mouths, the salinity is close to zero. Even in the Bothnian Sea, the salinity stratification is relatively weak, and overall oxygen conditions have remained fairly good, not to mention some specific coastal areas. However, oxygen conditions in the deepest layer have somewhat deteriorated over the recent 2 decades, although there is no real evidence that hypoxic conditions will occur in the future (Raateoja, 2013).

6 Climate variability and change – impact on salinity dynamics

6.1 Development of the mean salinity

The long-term changes in the salinity of the Baltic Sea depend to a large extent on net precipitation, river discharge, and wind forcing (Winsor et al., 2001, 2003; Meier and Kauker, 2003; Gustafsson and Omstedt, 2009); higher salinity appears during dry periods and lower salinity during wet periods. Furthermore, on shorter timescales, the mean salinity of the Baltic Sea is governed by the water exchange between the North Sea and the Baltic Sea, which is governed by the prevailing atmospheric conditions. Generally, westerly winds force inflow of saline water and easterly winds force outflow of brackish Baltic Sea water. Multi-decadal oscillations control the long-term variations of the surface salinity and its meridional gradient with a period of about 30 years (Radtke et al., 2020). A statistically significant positive trend of centennial changes in the north–south gradient of the surface salinity has been found (Kniebusch et al., 2019b). Increased river runoff from the most northern catchment could explain this trend. Observations reveal (Fig. 5, see Sect. 5.1) that after the minimum around 2003/04, the volume-averaged salinity increased again until 2018. Fluctuation in the accumulated anomalies of river runoff coincides with the variability in mean salinity, confirming the role of river runoff in controlling the mean salinity of the Baltic Sea (Kniebusch et al., 2019b; Radtke et al., 2020).

6.2 Internal circulation and stratification

The long-term salinity dynamics within the Baltic Sea are controlled by the large-scale internal water cycle (e.g., Elken and Matthäus, 2008). There is a surface layer circulation and a deepwater circulation decoupled in the Baltic Proper by the permanent halocline. The wind and freshwater surplus drive the upper layer circulation. It is mainly Ekman dynamics in combination with complex coastlines and upwelling and downwelling. In the lower layer, the flow, which is the dense bottom current, is driven by internal pressure gradients steered by the complex bottom topography consisting of deep basins and channels and restricted by sills (Leppäranta and Myrberg, 2009). The vertical branch of this circulation system, termed the Baltic Sea haline conveyer belt (Döös et al., 2004), is restricted by the strong permanent saline stratification. Convection, mechanical mixing, entrainment, and vertical advection determine the vertical salt flux across the halocline. It is not only the mean salinity of the Baltic Sea which varies over the years; there are also considerable changes in the strength of the permanent salinity stratification. Liblik and Lips (2019) found a strengthening of the permanent halocline in the deep basins of the Baltic Sea over the period 1982–2016. They argued that the accumulated river runoff probably caused the decrease in surface salinity. However, they found no correspondence between increased runoff and decreased surface salinity in the second half of the period (compare Figs. 4 and 5). They argued that changes in the vertical salt transport might be the reason for this, which might be related to changes in meteorological forcing. However, the volume-averaged salinity of the eastern Gotland Basin is highly correlated with the accumulated river runoff (Fig. 5). After the major inflow in January 1993, salinity increased in the lower layer of the eastern Gotland Basin (Fig. 2). This increasing trend of deep layer salinity (Fig. 3) due to stronger lateral salt transport from the Kattegat could not be explained by a growing number of barotropic and major Baltic inflows (Mohrholz, 2018). So, the reason for the change in the haline stratification in the deep basins of the Baltic Sea over the recent 3 decades remains unclear.

6.2.1 The specific role of precipitation and river runoff

River runoff (R) and net precipitation ($P-E$) over the sea surface are dominant drivers of the Baltic Sea salinity, together with the limited water exchange with the North Sea explaining the large gradient in sea surface salinity between about $20\,\mathrm{g\,kg^{-1}}$ in Kattegat and $2\,\mathrm{g\,kg^{-1}}$ in the Bay of Bothnian (Leppäranta and Myrberg, 2009). Net precipitation amounts to about 10 % of the total river runoff (e.g., Leppäranta and Myrberg, 2009; Meier and Döscher, 2002), even if there are some uncertainties in these estimations. For the period 1850–2008, the total river runoff from the Baltic Sea catchment area reconstructed from observations (Hansson et al., 2011; Cyberski and Wroblewski, 2000; Mikulski, 1986; Bergström and Carlsson, 1994) and hydrological model results (Graham, 1999) shows no statistically significant trend but a pronounced multi-decadal variability with a period of about 30 years (Meier et al., 2019a, b). According to model results, these variations in runoff explain about 50 % of the long-term variability of the volume-averaged salinity of the Baltic Sea (Meier and Kauker, 2003). This relationship is also confirmed for the period 1979 to 2018 presented in Fig. 5. The volume-averaged salinity of the eastern Gotland Basin is highly negatively correlated with the accumulated anomaly of runoff to the Baltic Sea. About 27 % of the interannual salinity variation is explained by the direct dilution effect (Radtke et al., 2020). In addition to the dominant 30-year period, there is a pronounced decadal variability of both mean salinity and accumulated anomaly of runoff, with the minima of mean salinity directly associated with the maxima in runoff anomaly. Furthermore, minima of mean salinities occur just before major saltwater inflows (MBIs) happen. Since about the 1970s, the mean seasonal cycle of the total river flow has changed with increasing and decreasing runoff during winter and summer (Meier and Kauker, 2003). These changes might be explained by river regulation of large rivers in the north and systematic changes in precipitation patterns due to warming in the Baltic Sea region. Blöschl et al. (2017) investigated the timing of river floods for the Baltic Sea catchment over the past 50 years and found changes in flood timing which can be related to climate change. Increasing temperatures have led to earlier snowmelt floods. However, the change in seasonality does not affect the total discharge trend. As there is no statistically significant trend in saltwater inflows on the centennial timescale (Mohrholz, 2018), changes in salinity are regionally limited. Furthermore, there is no statistically significant long-term trend in salinity (Fonselius and Valderrama, 2003). As a consequence of the pronounced 30-year variability in runoff and MBIs, the mean salinity shows these variations as well (Winsor et al., 2001, 2003). As part of the variability, during 1983–1993, a stagnation period without MBI and with decreasing salinity was observed (Nehring and Matthäus, 1991). Model results suggest that decreasing salinity over about 10 years appears approximately once per century on average and belongs to the natural variability of the system (Schimanke and Meier, 2016).

On longer timescales, the Baltic Sea salinity is under the influence of the AMO with a period of about 60–90 years (Börgel et al., 2018). Since about the 1980s, increased bottom and decreased surface salinities have been observed

(Vuorinen et al., 2015; Liblik and Lips, 2019), and an accelerated warming might be attributed to the AMO (Kniebusch et al., 2019a). Whether the recent salinity changes are connected to the AMO is still unknown.

Besides local effects on surface salinity, due to varying river runoff and net precipitation, there is an additional remote effect due to the accumulated volume of fresh water. This water volume has to leave the Baltic Sea as a brackish surface outflow through the Danish Straits. Periods of positive anomalies of freshwater input (P-E+R) lead to increasing outflow and a shift of the wedge-shaped salinity fronts in the Belt Sea and the Sound further in the direction of the Kattegat, indirectly impacting the compensating inflow of more highly saline water over Drogden and Darss sills. During negative anomalies of freshwater input, reduced outflow occurs, and the wedge-shaped salinity front moves further in the direction of the Darss and Drogden sills (Lehmann and Hinrichsen, 2000). As the net precipitation is of the order of 10 % of the total river runoff, wet years will lead to a decreased salt flux into the Baltic Sea, and dry years will lead to an increased salt flux.

6.2.2 The role of sea level change due to global warming

The northern areas in particular have experienced an acceleration of global warming during recent decades. The linear trend of global temperature increase shows warming of 0.85 °C over 1880 to 2012 (IPCC, 2020). The linear temperature rise for the Baltic Sea is about 0.4 °C per decade (e.g., Lehmann et al., 2011).

The absolute sea level rise of the Baltic Sea over the 20th century is about 1.3–1.8 $\mathrm{mm\,yr^{-1}}$, which is within the range of global estimates. In more recent decades, the basin-wide range of sea level rise may be around 5 $\mathrm{mm\,yr^{-1}}$ with a rather considerable uncertainty of $\pm 3\,\mathrm{mm\,yr^{-1}}$, which is even higher than the global mean sea level (GMSL) estimate of 3.2 $\mathrm{mm\,yr^{-1}}$ (Hünicke et al., 2015; Dangendorf et al., 2019). For more detailed information on sea level dynamics and coastal erosion in the Baltic Sea region see Weise et al. (2021).

Hordoir et al. (2015) investigated the influence of rising GMSL on saltwater inflows into the Baltic Sea. They performed idealized model sensitivity experiments using a regional ocean general circulation model covering the North Sea and the Baltic Sea. Hordoir et al. (2015) found a nonlinear increase in saltwater inflow intensity and frequency with rising GMSL. However, their explanation of reduced mixing in the Danish Straits was shown to be wrong (Arneborg, 2016). Arneborg (2016) proposed an alternative theory instead. Due to the smaller depth, the volume flux through the Sound is more sensitive to GMSL rise than that through the Belt Sea. Under present conditions, the amount of dense water passing the Drogden Sill in the Sound is determined by a baroclinic control in the narrow northern end of the Sound (Nielsen, 2001). With rising GMSL, this control is degraded, and relatively more saltwater is transported into the Baltic Sea compared to the expected increase when the transport change is proportional to the area of the limiting cross section. Assuming a negligible impact of GMSL rise, the intensity and frequency of MBIs were projected to remain unchanged, with a potential tendency of a slight increase (Schimanke et al., 2014). However, in future high-end global mean sea level projections, reinforced saltwater inflows result in higher salinity and increased vertical stratification compared to present conditions (Meier et al., 2017; Saraiva et al., 2019).

7 The impact of salinity dynamics on the environmental conditions of the marine ecosystem

7.1 Oxygen conditions

Generally, the Baltic Sea's oxygen distribution results from the input through the atmosphere–ocean interface, physical transport, and the consumption of oxygen due to respiration and biogeochemical processes. The layer above the halocline is well oxygenated due to vertical convection during winter. In and below the halocline, the ventilation happens only by horizontal advection of water originating from the Danish Straits and the Kattegat. In the deep basins below the halocline, there is often no sufficient oxygen supply so that continuous oxygen consumption leads to hypoxic or even anoxic conditions. In the Bothnian Sea and Bay of Bothnia (Fig. 1), the salinity stratification is weak so that vertical deep convection during winter has prevented these basins from experiencing oxygen deficiency so far.

Climate warming impacts not only the deepwater oxygen distribution. The solubility of oxygen at the surface depends on the water temperature. In warmer water, the solubility is reduced and oxygen consumption is increased by enhanced decomposition of organic matter. Thus, even after major saltwater inflows (MBIs), which can reach the deep basins of the Baltic Sea, improved oxygen conditions will turn back to hypoxic conditions faster than in former times (Naumann et al., 2018). The trend in oxygen depletion is about 0.1 $\mathrm{mL\,L^{-1}}$ per decade in the surface layer and up to 1 $\mathrm{mL\,L^{-1}}$ per decade in the halocline (Fig. 3).

7.2 Environmental impact on fish, larvae, and salinity dynamics

Roughly 100 fish species occur in the Baltic Sea. Their spatial distribution is primarily governed directly by salinity and oxygen. Marine species (~ 70 species) dominate in the central Baltic Sea, while freshwater species (30–40 species) mainly occur in coastal areas and the northeastern parts of the Baltic Sea (HELCOM, 2002). Cod, herring, and sprat comprise most of the fish community in biomass and numbers. The marine species sprat, herring, cod, various flatfish, salmon, and the freshwater species pike and perch are commercially important before severe stock declines (Nilsson et al., 2004).

Cod eggs in the Baltic Sea have a vertical distribution concentrated in deep water and near or below the permanent halocline (Wieland and Jarre-Teichmann, 1997). Thus, cod eggs are frequently distributed in water layers with very low oxygen concentration (Nissling et al., 1994; Wieland et al., 1994). The eastern Baltic cod has a prolonged spawning period from March to September (Köster et al., 2017). The reproductive layer thickness for eastern Baltic cod is limited to minimum environmental threshold values (salinity 11 g kg^{-1}, temperature 1.5 °C, and oxygen 2 mL L^{-1}; Wieland and Jarre-Teichmann, 1997; Nissling and Westin, 1991; Nissling et al., 1994; Wieland et al., 1994). The reproductive layer thickness for western Baltic cod in February–March (the peak spawning time of this stock) is limited to minimum environmental threshold values (salinity 16.5 g kg^{-1}, temperature 2 °C, and oxygen 2 mL L^{-1}; Nissling and Westin, 1997) to keep western eggs in the Arkona Basin floating to allow successful development and survival. In a modeling study, Hinrichsen et al. (2016a) showed that the spatial extent of the habitat suitable for successful fertilization and development of eggs of the eastern cod stock is primarily determined by oxygen and salinity conditions at spawning. The highest survival of eastern Baltic cod eggs occurred in the Bornholm Basin, with a pronounced temporal decrease in survival in the Gdansk Deep and the Gotland Basin. Relatively low survival in these areas was attributable to oxygen-dependent mortality. Compared to eggs spawned in these eastern spawning grounds, eggs spawned in the Arkona Basin were affected mainly by sedimentation, i.e., the lack of sufficiently saline water at the bottom to ensure successful egg fertilization and development. However, since the mid-2000s, a substantial increase in sedimentation-related mortality has also been observed for the Gdansk Deep (Hinrichsen et al., 2016a).

For the Bornholm Basin, Hinrichsen et al. (2016b) estimated the geographic extent of the area with hydrographic conditions suitable for egg development in the early (April–May), middle (June–July), and late (August–September) spawning season. Egg survival depends on their buoyancy, which is related to female age and/or size. Large eggs, for example, are spawned by large, old females and float at low water density. The seasonal timing of spawning does not matter for these large eggs, while small eggs spawned by young females sink towards the bottom and suffer higher mortality due to exposure to hypoxic conditions. The geographic area suitable for their survival is concurrently lower than for larger eggs, with the most favorable conditions occurring late in the spawning season owing to the summer inflows.

The Arkona Basin, a relatively shallow area (max depth ∼ 40 m) mainly occupied by the western Baltic cod stock, has recently also been utilized as spawning ground by the eastern cod stock (Bleil et al., 2009; Hüssy, 2011). Generally, the reproductive conditions appear to be more favorable for the eastern stock, with several occasions of relatively large reproductive layer thicknesses since 1999, which was extremely seldom for the western stock. Vertical resolution data on the reproductive layer thickness for both stocks showed improved reproductive conditions for eastern cod of about 10 m overall layer thicknesses in June to August since 2000. A certain fraction of the egg production of the eastern cod stock can be expected to sink to the bottom and die. However, in a combined stock identification and drift model study, Hüssy et al. (2015) showed that eastern Baltic cod have progressively immigrated into the Arkona Basin during recent years. This resulted in stock mixing with the western stock, showing a marked increase in proportion between 2005 and 2008 with a fairly stable proportion of approximately 70 %–80 % since then. Even though this stock mixing is purely a physical admixture without interbreeding (Hemmer-Hansen et al., 2019), the immigrating eastern cod may have contributed to the recruitment of the eastern cod stock in this management area. However, this was only possible for relatively late-spawning eastern cod in years characterized by specific conditions, i.e., after summer inflows of saline water. The decreasing surface salinities in the 1980s (see Sect. 5.1) led to a southward shift of the salinity range of 5–7 g kg^{-1}, which is the threshold for both freshwater and marine species distribution and diversity (horohalinicum). Vuorinen et al. (2015) discussed potential ecological consequences of varying surface salinity due to increased rainfall and river runoff. Species distribution and abundance will be affected favorably or negatively according to their origin. Decreasing surface salinity will lead to further expansion of freshwater species at the expense of marine species.

8 Present knowledge gaps

There is still a need to better understand the role of freshwater balance in salinity distribution and its variability on seasonal to interannual timescales. The surface salinity of the eastern Gotland Basin varied over the recent 4 decades (Fig. 4). In the 1970s, it started at relatively high values of about 7.5 g kg^{-1}, decreased until 2002, and slightly increased until 2018. There is a pronounced interannual variability of the surface salinity, which might be related to changes in the atmospheric forcing (wind and precipitation over the sea) and/or river runoff (Radtke et al., 2020). There is still research needed to better understand the development of salinity stratification and its role in increasing hypoxia as well as to evaluate the changes in atmospheric circulation and its impact on inflows and salinity distribution in the Baltic Sea. One key question is the complete mechanistic description of barotropic and major saltwater inflows: MBIs. Even if these have been studied for decades, we can question whether we really understand the process: can we predict MBIs? Extended outflow periods before the inflow reduce the mean sea level of the Baltic Sea and in parallel lead to the formation of a haline stratification in the Danish Straits with highly saline water propagating in the direction of Darss and Drogden sills. The frequency of low-pressure systems passing over the Baltic Sea and the strength of the wind will be enhanced for MBIs compared to LVCs. Thus, this leads to higher transport rates.

Forthcoming work needs to explore the chain of processes in detail, which in addition to large barotropic inflows leads to an influx of highly saline and oxygenated water. The freshwater input seems to play only a modulating role for the occurrence and strength of barotropic inflows. The total frequency of inflow events will not change, but the average amount of salt which an individual event transports into the Baltic Sea may change (Radtke et al., 2020). Both river runoff and the strength of barotropic inflow show variation on a 30-year timescale, and both show a stable and plausible phase relationship to be the driver of interdecadal salinity variations (Radtke et al., 2020).

Summer inflows of saline water masses can be traced in the Bornholm Basin by unusually high temperatures in the halocline zone. Warm and salty summer inflows belong to baroclinic inflows. They might result in higher connectivity between nursery areas of pelagic fish species west of their principal spawning grounds and spawning stocks, e.g., for Baltic cod and flounder (Ruzzante et al., 2006; Svedäng et al., 2007).

At the time of writing, detailed studies on summer inflows and how they might have changed over time are missing. There are also local processes that deserve further studies. Detailed assessments of the exchange between coastal areas, including lagoons and the open sea as well as between subbasins, the cold intermediate layer, and turbulent mixing, are still needed. Furthermore, the dynamics of small-scale variability, eddies, frontal regions, and vertical mixing are highly important for the salinity dynamics in total (e.g., Reismann et al., 2009). Studies focusing on small-scale variability affecting low-frequency variations in the Baltic Sea are not available. To improve our knowledge of these processes, we need detailed and joint modeling and observational studies.

One very topical issue, which is indirectly linked to salinity distributions, is the general circulation of the Baltic Sea. Do we understand all branches of the Baltic Sea haline conveyer belt? There are few regular observations of it, and the modeling exercises show significant discrepancies between results and observations.

9 Key messages

The long-term salinity dynamics are controlled by river runoff, net precipitation, and the governing east–west wind conditions, i.e., the water mass exchange between the North Sea and the Baltic Sea. Changes in runoff are highly correlated with the development of the mean salinity of the Baltic Sea and explain about 50 % of its variability (Fig. 5). A 30-year variability has been found for surface and bottom salinity, river runoff, and salt transport across the Darss Sill. There is no clear long-term trend of the mean salinity of the Baltic Sea, even if, during the last 40 years, surface salinity has decreased, and the lower layer salinity increased. This might be connected to changes in the vertical flux of salinity, but the explanation is still unclear.

Variations of salinity on shorter timescales (monthly to annual) are even more complex, especially in and below the halocline. Furthermore, there is a direct effect on temperature and salinity distributions. Stronger saltwater inflows can directly be traced by changes in the deepwater salinity and corresponding changes in temperature and oxygen (Fig. 2).

Over recent decades, negative salinity trends have appeared at the surface. At the same time, temperature is increasing and oxygen is decreasing. The linear trend ($\sim 0.4\,^{\circ}\mathrm{C}$ per decade) of the sea surface temperature of the Baltic Sea is about the same as the air temperature trend.

The decreasing trend in oxygen can partly be explained by increasing temperatures, which affect oxygen solubility and depletion rates. Maximum negative trends up to $1\,\mathrm{mL\,L^{-1}}$ per decade can be found in the halocline of Bornholm and Gotland Basin (Fig. 3).

The major saltwater inflow in December 2014 stimulated new research to revisit the barotropic water exchange between Kattegat and the Baltic Sea.

The major saltwater inflows (MBIs), which occur in response to specific atmospheric circulation patterns, can be regarded as a subset of barotropic inflows or large volume changes. Atmospheric forcing is more strongly associated with LVCs than MBIs, while it directly controls the sea level and indirectly the amount of salt of the inflowing water mass.

The strength of the inflows and the amount of salt transported into the Baltic Sea depend on the intensity of the wind and the haline stratification in the Danish Straits.

It has been widely speculated that MBIs play the most crucial role in the development of deepwater salinity. Still, recent studies show that the frequency of major saltwater inflows did not change. So, the associated worsening of bottom oxygen conditions is caused by climate warming, excessive nutrient loading, related oxygen consumption, and maybe increased stratification. This strongly suggests that reducing the external nutrient load to the Baltic Sea is still highly needed to improve its ecological state.

At regional scales, in addition to the interaction with the main Baltic Sea, the salinity regime of estuaries and lagoons is closely related to the local water balance components, including river runoff, precipitation, and evaporation. So, in the changing climatic conditions, the development of the salinity regime at regional scales may have various basic-specific features that might diverge from corresponding trends in the main Baltic Sea. This fact will lead to high demand to carry out basin-specific studies to understand the changes in the local salinity regime.

Finally, we can summarize our present knowledge of salinity dynamics as follows. There is now a better overall view of the salinity of the Baltic Sea than before: not only the fragments on various scales of time and space are known. The measurements have also given an improved view on the regional scale in gulfs and lagoons, not only in the central part of the sea or some volume-averaged case. Future projections exist, but they still have a lot of uncertainties. The temporal variability can now be divided between the decadal and smaller scales.

Data availability. This work is a review based on already published papers. There is no reference to additional data sets. Data for the figures are based on data from the ICES Marine Data Centre (https://www.ices.dk/Pages/default.aspx; ICES, 2022) and http://helcom.fi/baltic-sea-trends/environment-factsheets (HELCOM, 2022) (HELCOM fact sheets).

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