Salinity dynamics of the Baltic Sea

– BEAR Report –

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Abstract

The salinity in the Baltic Sea is not only an important topic for physical oceanography as such, but it also integrates the complete water and energy cycle. It is a primary external driver controlling ecosystem dynamics of the Baltic Sea. The salinity dynamics is driven by: net precipitation, river runoff and the water mass exchange with the North Sea, with outflow from the Baltic Sea due to freshwater surplus and compensating inflow of higher saline waters from the Kattegat in deeper layers. The factors altering salinity are strongly controlled by the prevailing atmospheric forcing conditions. Since the Baltic Sea ecosystem has adapted to the present salinity regime, changes would induce noteworthy stress on marine fauna and flora with associated negative social-economic consequences for the Baltic Sea countries.

Despite the long history of Baltic Sea research, our present understanding of spatio-temporal variability of salinity is still limited, and future projections of the salinity evolution are even more uncertain. Thus, detailed investigations on atmospheric variability (wind forcing, regional precipitation patterns , including runoff, saline water inflows, the exchange between the sub-basins and processes contributing to the vertical mixing are needed.

Since BACC II book, which was published in 2015, collecting mostly research results until 2012, there has been new research on the salinity dynamics of the Baltic Sea stimulated e.g. by the Baltic

Earth network. Especially, after the recent Major Baltic Inflow (MBI) in December 2014 several new studies emerged. The research focused on key topics such as: the interrelation between decadal climate variability and salinity which includes detection and attribution to climate change, the water mass exchange and MBIs, and associated atmospheric conditions, salinity variability and fluxes on different scales, and associated changes in the circulation of the Baltic Sea.

1. Introduction

The salinity in the Baltic Sea is not a mere oceanographic variable, but it integrates the complete water and energy cycle which also has Baltic-specific features. Salinity, especially its low basic value and its large gradients , is an elementary factor controlling the ecosystem of the Baltic Sea. The salinity dynamics is governed by several factors: net precipitation, river runoff, surface outflow of brackish Baltic Sea water and the compensating deep inflow of higher saline waters from the Kattegat. The latter is strongly controlled by the prevailing atmospheric forcing conditions. In addition, the salinity dynamics is dictated by irregular barotropic exchange flows such as MBIs (Major Baltic Inflows, Matthäus and Franck, 1992) and LVC (Large volume changes, Lehmann et al., 2017) which have a great impact on stratification conditions and oxygen dynamics.

Even if the Baltic Sea physics has been investigated for a long time, our present understanding of spatio-temporal salinity changes is still limited. Not surprisingly, future projections of the salinity evolution are rather uncertain. Due to the projected increase in precipitation during the coming decades, scenario studies indicate a decrease in salinity of about 0.6 g/kg in the ensemble mean until the end of the century if the global sea level rise is neglected (Saraiva et al., 2019b). Since the Baltic Sea ecosystem has adapted to the present salinity regime, expected changes would exert a considerable stress on marine fauna and flora with associated negative social-economic consequences for the Baltic Sea countries (e.g. Vuorinen et al. 2015).

Since BACCII (BACC II Author Team, 2015, Elken et al. 2015), collecting mostly research results until 2012, new research has been carried out on the salinity dynamics of the Baltic Sea stimulated e.g. through the Baltic Earth network. Especially, after the recent MBIs in December 2014, and in 2015 and 2016, several new studies emerged on that (e.g. Mohrholz, 2015, Gräwe et al. 2015, Rak, 2015). The research focused on key topics such as: the interrelation between decadal climate variability and salinity, the barotropic water mass exchange and MBIs, and the associated atmospheric conditions, salinity variability and fluxes on different scales (detection and attribution to climate change), changes in the salt budget, and associated changes in the circulation of the Baltic Sea and resulting oxygen conditons (Kulinski et al. BEAR GC 2).

The paper is organized as follows. First, we summarize the knowledge which has been collected and summarized in BACC I (BACC 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 the description of 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 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 climate change impact on salinity dynamics. Following that, oxygen conditions are reviewed in the deep basins of the Baltic Sea, directly coupled to the salinity dynamics. Thus, an improved understanding of the salinity dynamics will also improve our understanding of the oxygen dynamics. Additionally, the salinity dynamics is also related to the environmental conditions of the marine ecosystem, like fisheries, etc., in the Baltic Sea which is discussed, too. The paper ends with discussing existing knowledge gaps and by giving key messages of our present understanding of salinity dynamics and suggesting necessary further work.

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

Salinity dynamics has 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 here the earlier findings of salinity dynamics in order to set up the basis of current understanding:

- The mean salinity of the Baltic Sea decreased during the early 20th century and again during the 1980s and 1990s, the latter is coupled with a complete lack of MBIs during 1983-1993. Common to these periods were stronger than normal freshwater inflow and zonal wind velocity showing a very long-term natural variability in the highly dynamic system. During the low-salinity phase, the deep water of the Gotland Basin was poorly ventilated, this leading to oxygen depletion, but at the end of the stagnation period, the hypoxic area was shrinking because of the deeper halocline. In the Gulf of Finland even the halocline vanished, and the bottom oxygen conditions improved . However, it is worth to notice that no long-term trend was found for the vertical mean salinity if the entire 20th century is considered.

- Recent 2-3 decades are characterized by slightly lower than normal top-layer salinity, supposed to be driven by higher accumulated river runoff,
- MBIs, usually of barotropic origin, occur in favorable meteorological conditions during winter and spring when easterly winds are followed by strong westerly winds for several weeks. The back-to-back occurrence of these two wind events is not very common in the Baltic Sea. This keeps the natural frequency of MBIs relatively low.
- Since 1996, summertime baroclinic inflows have been observed; these transport high-saline, but warm and low-oxygen water into the deep layers of the Baltic Sea. Such events have, most probably, occurred also before, but have not been observed due to shortcomings in observational systems.

3. Atmospheric forcing driving the salinity dynamics of the Baltic Sea

Atmospheric circulation, to a large extent, controls patterns of water circulation and biophysical aspects relevant for biological production, such as the vertical distribution of temperature and salinity, alterations in weather regimes may severely impact the trophic structure and functioning of marine food webs (Lehmann et al., 2002; Hinrichsen et al. 2007).

The speed and position of the Atlantic storm track or the polar jet stream is the most prominent feature that influences the variability in the atmospheric circulation in the Baltic Sea region. The influence of this storm track could be described in various scales of space and time. The larger scales play an important role in the developing of the mean state of salinity, while the smaller scales are important for shorter-term events like LVC-s. Starting from the largest, the continental or hemispheric scale, teleconnection patterns are commonly used to describe atmospheric circulation variability. The best-known of them is the North Atlantic Oscillation (NAO), which is the first mode of principal component analysis of sea level pressure (SLP) field over the North Atlantic/European sector (Hurrel, 1995). The second mode is called the East Atlantic (EA) pattern (Wallace and Gutzler 1981), the third dominant mode is the Scandinavian pattern (SCA), also called the Eurasian or blocking pattern (Hurrel and Deser 2009). All these modes are better expressed in winter than in other seasons.

The complex water exchange between the North Sea and the Baltic Sea is often related to the NAO index, or some similar local index (e.g. BSI – Baltic Sea Index, Lehmann, et al. 2002) that shows the strength of the zonal atmospheric circulation. The popularity of the NAO came from its ability to describe 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) and the NAO index was very high (Lehmann et al.

2017). But after the 1990-s, due to the non-stationarity of this correlation, this simple approximation did not work anymore (Lehmann et al. 2017). The latter is associated with the considerable changes in intensification and location of storm tracks, in parallel with the eastward shift of the NAO centers of action, that was highlighted from the analysis of winter SLP data (Lehmann et al 2011). Additionally, a seasonal shift of strong wind events from autumn to winter and early spring exists for the Baltic area.

The strength of windstorms is certainly important for salinity dynamics. Zubiate et al. (2016) characterized variability of wind speeds and distribution as a function of the NAO and the contemporary states of the secondary (EA) and tertiary (SCA) patterns of the SLP variability over the whole of Europe. Strong correlations at monthly time scales have been found between the NAO positive phase and wind speeds in northern Europe. But this effect combines with different other patterns, that vary with subregion. 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 important player in wind climatology, is also found to have 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 southern flank of the Baltic Sea (Waltz et al., 2018). All this refers that from the viewpoint of large-scale atmospheric variability, the Baltic Sea region is not homogeneous. Thus, it is necessary to investigate forcing patterns also at smaller scales.

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. Both kinds of approaches are used to characterize atmospheric forcing before, during, and after the events of large barotropic inflows or large volume changes (LVC, Lehmann, et al. 2017). From earlier studies could be deduced that during these events synoptic-scale atmospheric forcing, that could be easily represented and interpreted using automated weather types, is important. Two different synoptic classifications have been used (Lehmann and Post, 2015; Post and Lehmann, 2016). During different phases of the inflow, the abundance of certain classes (directions of synoptic-scale airflow) increases or decreases compared to the average frequency of classes. About 60 days before the maximum sea surface elevation (SSE) at Landsort, i.e. maximum inflow, the frequency of eastern and southeastern classes increased for about 30 days, which confirms the idea of Matthäus and Schinke (1994) about the pre-inflow period for which easterly winds prevail pushing the water out of the Baltic Sea, lowering the mean sea level and hindering the inflow of North Sea water through the Danish Straits. The associated anticyclonic circulation is related to dry periods with less precipitation and increased saline stratification in the Belt Sea area. An immediate period of strong to very strong westerly winds, starting about 30 days before the maximum SSE, trigger the inflow and force effective LVCs/MBIs. Atmospheric forcing is more strongly associated with LVC-s than MBI-s, while it controls the sea level, not the salinity abundance.

The main idea is that events like LVC-s/MBI-s depend on the sequence or accumulation of forcing which is not easy to follow by an Eulerian-type approach, the tracking of cyclone pathways and classifying of pressure field sequences helped to overcome this kind of problems. Lehmann et al. (2017) studied pathways of deep cyclones associated with large volume changes in the Baltic Sea. The average duration of LVCs was about 40 days. During this time, 5–6 deep cyclones moved along characteristic storm tracks. The conditions for LVCs to happen were temporal clustering of deep cyclones in certain trajectory corridors.

One possible reason for less frequent MBIs in the 1980s might be the increased atmospheric zonal circulation linked with intensified precipitation in the Baltic region and increased river runoff to the Baltic (Schinke and Matthäus 1998; Lehmann et al 2002; Meier and Kauker 2003; Lehmann, et al 2011). An alternative explanation has been proposed by Soomere et al. (2015). They found a significant abrupt change in the meridional component of the air-flow direction over the southern Baltic Sea around 1987. This change is established by a substantial increase in north-western wind events at the expense of other wind directions (e.g. western winds that are critical for MBIs to occur).

4. Update of the knowledge of salinity dynamics since 2012

4.1 Large volume changes and Major Baltic Inflows

The water exchange between the Baltic Sea and the North Sea through the Danish Straits is, despite of the long history of research, a topical issue because the complex dynamics is still not fully understood. Furthermore, the salinity variability in the central Baltic Sea depends on the occurrence of major saltwater inflows. These can be understood as a subset of barotropic inflows which happen in response to a specific sequence of atmospheric circulation patterns (e.g. Matthäus et al. 2008, Leppäranta and Myrberg, 2009; Lehmann and Post, 2015), and clustering of deep cyclones in space and time (Lehmann et al., 2017). The atmospheric viewpoint from these studies was recently extended by investigating the impact of the hydrographic conditions in the Danish Straits and the total freshwater supply to the Baltic Sea prior to the inflow event on the occurrence of highly saline barotropic inflows, so-called Major Baltic Inflows (MBIs). A mechanistic explanation was proposed that included both the salinity in the Danish Straits, and the evolution of the atmospheric forcing during the inflow period. Fresh water supply played only a modulating role, i.e. it does not lead to a change in frequency nor intensity of the events, but modulated the salt transport into the Baltic Sea (Höflich and Lehmann, 2018).

Triggered by the exceptional MBI in December 2014 (e.g. Mohrholz et al., 2015, Gräwe et al. 2015, Rak, 2016, Neumann et al. ,2017, Liblik et al., 2017), the MBI time series was revisited (Mohrholz, 2018). Using long term data series of sea level, river discharge, and salinity from the Belt and Sound a continuous time series of barotropic inflows was constructed for the period from 1890 till present. A comparison with the MBI time series of Fischer and Matthäus (1996) revealed significant differences in the period since the 1980ies. The reasons for these deviations, between both time series, are mainly due to lack of appropriate data between 1976 and 1991, and the change in observation methods afterwards, which caused a bias in the inflow statistics in addition to the changes in locations of the observations (Mohrholz, 2018). The inflow events in the revised MBI time series was termed DS5. In contrast to earlier investigations, the revised MBI time series (DS5) depicts no significant long-term trend in MBI frequency and intensity, contradicting the hypothesis that climate change caused a decreasing MBI frequency. However, there exists a decadal variability of large barotropic inflows with a main period 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 Darss Sill (Radtke et al. 2020). Smaller barotropic inflow events occur throughout the year with low interannual variability and supply on average 30% of the total salt transport into the Baltic. The observed temporal variability of barotropic inflows of saline water does not explain the increasing stagnation periods in the Baltic Sea deep water and the spread of anoxic bottom conditions in the central Baltic Sea (Mohrholz, 2018). Large barotropic inflows and the associated dense bottom currents form one branch of the Baltic Sea overturning circulation and deep-water ventilation. Holtermann et al. (2017) investigated the deep-water dynamics and mixing process during major inflow events in the central Baltic Sea; thus, providing new information on dense bottom gravity currents on its way to the deep central Baltic Sea and associated turbulent mixing. Liblik et al. (2018) studied the impact of MBIs downstream from the eastern Gotland Basin to the Gulf of Finland. In a further study using satellite altimetry data, Stramska and Aniskiewicz (2019) showed that remote sensing altimetry can be used as a complementary source of information about barotropic inflow events.

4.2 The cold intermediate layer

A specific feature of the Baltic Sea is the annual formation of the so-called Cold Intermediate Layer (hereafter denoted as CIL). CIL appears as a temperature minimum between the thermocline and the permanent halocline during spring to autumn. Vertical convection, due to cooling of the atmosphere, and wind mixing erodes 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 (Fig. 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 almost every winter to a complete turnover of the entire water column (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., 2007; Liblik and Lips, 2011). However, 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., 2007; 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 higher saline water. This buoyancy flux is stronger than the destabilizing effect caused by the warming of the water, when $T < T_{md}$ (Chubarenko et al., 2017; Eilola and Stigebrandt, 1998). According to Chubarenko and Stepanova (2018), colder and slightly saltier water, that has its origin from the upper layer of the Bornholm Basin, advects to the east and forms the core of the CIL. 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 have 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

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 of the Baltic Sea. The salinity dynamics of the eastern Gotland Basin is also affecting the different sub-basins and lagoons surrounding it. The Gotland deep (the deepest part of the eastern Gotland Basin) is a representative location for describing salinity and stratification development within the Baltic Sea as a whole. Indeed, changes in mean salinity calculated from Gotland deep data, are only 2% different to changes calculated based on data from all sub-basins (Winsor et al 2001, Winsor et al. 2003, Elken et al. 2015). Observed surface salinity of the eastern Gotland Basin (Fig. 2 and Fig. 4) reveal 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 is slightly increasing and fluctuating until 2018, but it remains on a relatively low level (< 6.5 g kg^{-1}; Fig. 4). The deep water salinity decreased from the late 1970s until 1993 and then increased until 2018 (Fig. 2). Major salt water 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) which keep the salinity below the halocline on a high level (Fig. 2). Over recent decades, negative salinity trends of about 0.1-0.2 g/kg/decade appear at the surface, 0.4-0.6 °C/decade for temperature and 0.1-0.2 ml/l/decade for oxygen. The temperature trend is about the same as the air temperature trend. The trend in oxygen is strongly related to the increasing temperatures (changing solubility and oxygen depletion rates) with maximum negative trends up to 1 ml/l/decade in the area of the halocline (Bornholm and Gotland Basin, Fig. 3). For the negative trend of surface salinity, it is assumed that runoff and net precipitation play a role. However, in deeper parts the salinity trend (0.2-0.25 g/kg/decade) is reversed Liblik and Lips (2019), although the frequency of barotropic and major saltwater inflows did not increase. The volume averaged salinity shows also a drop until 1992, and with the MBI in 1993 a gentle increase occurred (Fig. 4 and Fig. 5).

5.2 Salinity dynamics of the Gulf of Finland

The Gulf of Finland is an elongated sub-basin of the Baltic Sea locating in the north-eastern 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, the maximum depth being 123 m (in the Baltic Sea 459 m). The drainage area of 420 990 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 locates; namely river Neva. The water column can be divided into three layers – the upper mixed layer, the cold intermediate layer (CIL), and the sub-halocline near-bottom layer separated by the seasonal thermocline and the quasi-permanent halocline, respectively (Alenius et al., 1998, 2003; Soomere et al., 2008). The seasonal thermocline vanishes on 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 g kg^{-1} in the easternmost part to 6 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) as a result of the general cyclonic circulation scheme (Andrejev et al., 2004a, b). The westward flowing current along the northern coast is changing 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 up- 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 intensify the transport of fresher waters to the west (Elken et al., 2003; Liblik and Lips, 2012), shallow the mixed layer 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 up- 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 in the southern/northern coast have several distinctive characteristics. Less wind forcing is needed to generate upwelling along the southern coast compared to 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 detected in the upwelling favorable winds in 1982-2013 (Liblik and Lips, 2017).

First 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 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 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. Salinity maximum/minimum usually occurs in the deep/surface layer in summer, when vertical mixing is restricted by the seasonal thermocline, and westerly winds are not that dominant. Another minimum in the sea surface salinity might occur due to lack of vertical mixing in the ice-covered areas in late winter (Merkouriadi and Leppäranta, 2015).

Multi-year changes of salinity in the deep layer are depending 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 decreased in the deep layer of the gulf (Lessin et al., 2014). After the recent MBIs (Naumann et al., 2018) salinity peaked at 10.77 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, that origins 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 occurrence of the inflow (Liblik et al., 2018).

Decadal trends of salinity show distinct changes vertically. Surface salinity decrease since the early 1980s has been estimated to be in the range from 0.005 g kg^{-1} (Liblik and Lips, 2019) to 0.02 g kg^{-1} per year (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 Fig. 2 and Fig. 4). However, the surface salinity increased by 0.5 g kg^{-1} during 1927-2012 in the north-western 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 g kg^{-1} per year over the period 1982-2016 (Liblik and Lips, 2019).

5.3 Salinity dynamics of the Gulf of Bothnia

The mean depth of Gulf of Bothnia is 55 metres and its surface area is 30 % of the entire Baltic Sea. The Gulf of Bothnia is an embedded semi-enclosed Baltic Sea basin where the hydrography is quite different from that in the other parts of the Baltic Sea (Fig. 1). This is because sills and archipelagos in the southern section largely isolate the basin from the Baltic Proper. The sill between Åland Sea and Baltic Proper prevents the northward propagation of deep water flow. It is assumed that the Bothnian Sea is 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. In the Åland Sea the surface salinity is 5.25–6.25 g kg^{-1} whereas at the depth of 200 meters the salinity varies between 7 and 7.75 g kg^{-1} . The lower layer water mass in the Åland Sea, as in the Sea of Bothnia, originates mostly from the upper homohaline layer of the Northern Baltic Proper, however, a small fraction of more saline deep-water flows in over sills. Sometimes in the near-bottom layer saline water can flow in through the Åland Sea to the Sea of Bothnia, and a corresponding volume of fresher water flows out to the Gotland Basin. This strengthens the stratification in the Sea of Bothnia (Leppäranta and Myrberg, 2008).

In the Sea of Bothnia (Fig. 1), the surface salinity varies between 4.8 and 6.0 g kg^{-1} and in the lower layer at 150 metres depth the salinity is 6.4–7.2 g kg^{-1} In the Bay of Bothnia (Fig. 1), the salinity is between 2 and 3.8 g kg^{-1} and at 100 metres depth near the bottom it varies between 4 and 4.5 g kg^{-1}. The Gulf of Bothnia has many rivers, and near the river mouths the salinity is close to zero.

The salinity stratification, even in the Sea of Bothnia, is relatively weak and overall oxygen conditions have remained relatively good, not to mention some specific coastal areas. To be accurate, the oxygen conditions in the deepest layers of the open Bothnian Sea have somewhat deteriorated during the recent two decades. However, there is no real evidence that the hypoxic events could appear there in the nearest future (Raateoja et al. , 2013). For consistent hypoxic events to emerge, the climate of the northern hemisphere would have to force profound changes in the hydrographic regime of the Baltic Sea. As the emergence of hypoxic events does not seem likely in the nearest future, there is no reason to expect that the internal loading of phosphorus will occur in the offshore Bothnian Sea. Considering the utmost importance of this phosphorus source to the past adverse development of the Gulf of Finland, it is apparent that the Bothnian Sea will not follow the example of the Gulf of Finland regarding eutrophication (Raateoja et al. , 2013).

5.4 Salinity dynamics of the Gulf of Riga

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 the 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 layer and the deep layer is only 0.7-1.0 g kg^{-1} (Raudsepp, 2001; Skudra and Lips, 2017). There is quite a high correlation between the river run-off in spring and the 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 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; Fig. 2 and 4).
The transport of saltier water from the Irbe Strait and the advection of riverine water is modified by wind-driven processes (Liblik et al., 2017; Lips et al., 2016b, 2016c; Soosaar et al., 2014, 2016). Most of the freshwater from the Daugava River is transported to the north along the eastern shore during the 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 favorable 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 sub-surface 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).

5.5 Salinity dynamics of lagoons

Coastal lagoons are shallow water bodies, separated from the ocean or sea by a narrow spit, bar or tombolo, and connected, at least intermittently, to the sea by one or more restricted inlets. Lagoons represent nearly 13% of the shoreline globally and around 5% in European seas (Lillebø et al., 2015). Some of the largest European lagoons (e.g., Curonian Lagoon, Vistula Lagoon, Szczecin Lagoon) situate in the Baltic Sea (Fig. 1). As the Baltic Sea can be considered as 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 which is 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, sea water 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 south-eastern lagoons of the Baltic Sea was 0.03 °C $year^{-1}$ in the period 1961–2008 and about 0.05 °C $year^{-1}$ 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 ∼4 mm $year^{-1}$ (Dailidiene et al., 2011). Also human activities, such as deepening of port areas/inlets, construction of infrastructure, river water regulation, intensive navigation, etc., directly affect the water balance and thus the salinity dynamics of the lagoons.

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 km^3 $year^{-1}$ to 33 km^3 $year^{-1}$ (Jakimavičius et al., 2018) with the dominant contribution from the Nemunas river. The total river runoff to the lagoon is on average about 22 km^3 $year^{-1}$, and it exhibits a strong seasonal pattern, peaking with snow melt during the flood season in February-April (Jakimavičius et al., 2018). The theoretical residence time of water in the Curonian Lagoon is about 80 days. The salinity in the southern and central parts of the lagoon, directly influenced by river waters, is up to 0.05 g kg^{-1}, while in the northern part, it is fluctuating between 0 and 7.5 g kg^{-1}. The annual mean salinity in the northern part of the Curonian Lagoon is increasing due to anthropogenic influence, i.e. dredging. The salinity distribution and fluctuations are mostly linked to the meteorological conditions that determine the inflow of saline water from the Baltic Sea. For example, winds blowing from north and north-east may lead to an inflow of saltier waters into the lagoons. During upwelling, Baltic sea water can reach the central Curonian Lagoon part even 40 km from the entrance. Climate change projections reveal an increase of the Curonian Lagoon’s salinity, which can be 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 the average salinity of 3.5 g kg^{-1}, and the salinity may vary from 0.5 g kg^{-1} in the southern part up to 6.5 g kg^{-1} at the Baltyisk Strait. The water balance of the Vistula Lagoon was estimated by Rózyn´ski et al. (2018): yearly, 17 km^3 (80.2%) of water enter the lagoon through the Baltyisk Strait, riverine inflows amount to 3.62 km^3 (17.1%), atmospheric precipitation 0.5 km^3 (2.4%), evaporation 0.65 km^3 (3.1%), and groundwater inflows 0.07 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 nineteenth century, evolving from a freshwater coastal lake to an estuarine lagoon with predominant marine influence (Chubarenko et al. 2017). There exist plans for the construction of a second inlet to the lagoon at the Polish side (Rózyn´ski et al., 2018), that could change the water balance of the lagoon in future.

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

Future changes in climate system components may have strongest effect on water salinity balance in the Baltic Sea coastal areas, such as lagoons. The sea-surface temperature in Curonian Lagoon is projected to increase by 2–6°C by the year 2100 (Jakimavičius et al., 2018). Water temperature and sea level rise in turn 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 increase in salinity in the lagoons.

6. Climate variability and change – impact on salinity dynamics

6.1 Development of the mean salinity

While the thermal response of the Baltic Sea to changes in air temperature is similar to that of a large lake, freshwater discharge from land and restricted water exchange with the North Sea create strong salinity stratification, accompanied by along-basin gradients such as those seen in estuaries and fjords (Kniebusch et al., 2019b). The long-term changes in salinity of the Baltic Sea depend to a large extent on net precipitation, river discharge and wind (Winsor et al. 2001, 2003; Meier and Kauker 2003; Gustafsson and Omstedt, 2009); with higher salinity during dry periods and lower salinity during wet periods. Salinity is also governed by the variability of the water exchange between the North Sea and Baltic Sea which by itself is governed by the prevailing atmospheric conditions. The long-term variability of the sea surface salinity and its latitudinal gradient is dominated by multidecadal oscillations with a period of about 30 years, while both atmospheric variables, wind and river runoff, contribute to this variability (Radtke et al., 2020). Centennial changes show a statistically significant positive trend in the North-South gradient of sea surface salinity for 1900–2008. This change is mainly attributed to increased river runoff from the northernmost catchment (Kniebusch et al. 2019). Observations reveal (Fig. 5, see also chapter 5.1) that after the minimum around 2003/2004 the volume averaged salinity increased again until 2018. Fluctuation in the accumulated anomalies of river runoff coincide with the variability in mean salinity confirming the role of riverrunoff in ontolling the mean salinityf the Baltic Sea (Kniebusch et al., 2019; Radtke et al. 2020).

6.2 Internal circulation and stratification

The long-term salinity dynamics within the Baltic Sea is controlled by the large-scale internal water cycle (e.g. Elken and Matthäus, 2008). There is a surface layer circulation and a deep-water circulation which are decoupled in the Baltic Proper by the permanent halocline. The upper layer circulation is driven by the wind and freshwater surplus. It is mainly of Ekman dynamics in combination with complex coastlines and up- and downwelling. In the lower layer, the flow, 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 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 is varying over the years, there are also considerable changes of 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 decrease in surface salinity was probably caused by the accumulated river runoff. However, they found no correspondence between increased runoff and decreased surface salinity in the second half of the period (compare Fig. 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) which is due to stronger lateral salt transport from the Kattegat cannot be explained by an increasing number of barotropic and Major Inflows (Mohrholz, 2018). So, the reason for the change of the haline stratification in the deep basins of the Baltic Sea over the recent 3 decades remains unclear.

6.3 The specific role of precipitation and river runoff

River runoff and net precipitation (precipitation minus evaporation) over the sea surface are dominant drivers of the Baltic Sea salinity, explaining together with the limited water exchange with the North Sea the large gradient in sea surface salinity between about 20 g kg^{-1} in Kattegat and 2 g kg^{-1} in the Bothnian Bay (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, Meier et al. 2019b). According to model results, these variations in runoff explained about 50% of the long-term variability of 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 30 years period (Meier et al. 2018) 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 salt water 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, respectively (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. However, as the change in seasonality does not affect the total discharge trend and as there is no statistically significant trend in saltwater inflows on centennial time scale (Mohrholz, 2018), changes in salinity are regionally limited and there is neither any statistically significant long-term trend in salinity (Fonselius and

Valderrama, 2013). 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 ten years appear approximately once per century on average and belongs to the natural variability of the system (Schimanke and Meier, 2016).

On longer time scales, 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 accelerated warming due to the AMO (Kniebusch et al., 2019). Whether the recent salinity changes are connected with 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 which is due to the accumulated volume of fresh water. This water volume has to leave the Baltic Sea as brackish surface outflow through the Danish Straits. Periods of positive anomalies of fresh water input lead to increasing outflow and a shift of the wedge-shape salinity fronts in the Belt Sea and the Sound further in direction to the Kattegat indirectly impacting on the compensating inflow of higher saline water over Drodgen and Darss sills. During negative anomalies of fresh water input, reduced outflow occurs, and the wedge shape salinity front moves further in direction to Darss and Drodgen sills (Lehmann and Hinrichsen, 2000). As the net precipitation is in 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.

6.4 The role of sea level change due to global warming

Since the mid-1980s an acceleration of climate warming has occurred with an associated temperature increase of about 0.17°C per decade. This trend is equally evident for many areas on the globe, especially in the northern hemisphere in observations and climate simulations (Trenberth et al. 2007). For the Baltic Sea catchment, which lies between maritime temperate and continental subarctic climate zones, an even stronger warming of about 0.4°C per decade has occurred since 1980 (e.g. Lehmann et al. 2011).

The absolute sea level rise of the Baltic Sea over the twentieth century is about 1.3 – 1.8 mm per year, which is within the range of global estimates. In more recent decades the basin wide range of sea level rise may be around 5 mm per year with a rather large uncertainty of ± 3 mm per year, even higher than the global mean sea level (GMSL) estimate of 3.2 mm per year (Hünicke et al. 2015, Dangendorf, 2019).

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 non-linear 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., 2019b).

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

7.1 Oxygen conditions

The O_2 conditions in the Baltic Sea are the result of two main factors: physical transport of O_2 and consumption of O_2 by biogeochemical processes. Owing to the positive freshwater budget and the bathymetry of the Baltic Sea, a strong vertical salinity gradient generates a permanent density stratification (pycnocline) that inhibits the vertical exchange of O_2 between the surface and deep waters. Lateral intrusions and inflows below the pycnocline, which is located at about 70 m in the central Gotland Basin, are the only effective means of O_2 transport. The inflowing water requires a density high enough to sink down to the near-bottom layers of the central Baltic Sea deep basins. Those inflows occur irregularly, sometimes at intervals of many years (e.g. Mohrholz, 2018). During longer periods, without a sufficient supply of O_2 to the deep water, the continuous consumption of O_2 by decomposition of organic matter results in O_2 depletion and eventually in the development of hypoxic and later on of even anoxic conditions. The most northern parts of the

Baltic Sea, the Bothnian Sea and Bothnian Bay (Fig. 1), are characterized by weaker density stratification, and vertical ventilation by deep convection may occur in particular years. Owing to the vertical ventilation and a lower primary production, this part of the Baltic Sea so far is not affected by O_2 deficiency.

Climate warming impacts on the deep-water oxygen distribution. The solubility of oxygen at the surface depends on the water temperature. In warmer water the solubility is reduced. Furthermore, oxygen consumption is increased by enhanced decomposition of organic matter. Thus, even after major salt water inflows, which are able to reach the deep basins of the Baltic Sea, improved oxygen conditions will faster turn back to hypoxic conditions than compared to former times (Naumann et al. 2018). The trend in oxygen depletion is about 0.1 ml/l/decade in the surface layer and up to 1 ml/l/decade in the halocline (Fig.3).

7.2 Environmental interaction between fish/larvae and salinity dynamics

Roughly 100 fish species occur in the Baltic Sea. Their spatial distribution is largely 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 in the north-eastern parts of the Baltic Sea (HELCOM, 2002). Cod, herring and sprat comprise most of the fish community in biomass and numbers. Commercially important are the marine species sprat, herring, cod, various flat fish, salmon, and the freshwater species pike and perch prior to severe stock declines (Nilsson et al., 2004).

Cod eggs in the Baltic Sea have a vertical distribution which is 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; Wieland and Jarre-Teichmann, 1997; Westin and Nissling, 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^{-}, temperature = 2°C, and oxygen 2 ml/l; 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. Highest survival of Eastern Baltic cod eggs occurred in the Bornholm Basin, and a pronounced temporal decrease of survival in the Gdansk Deep and in 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 mostly affected 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 strong 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 early (April-May), mid (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. For these large eggs the seasonal timing of spawning does not matter, while for 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 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 presently 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 seldomly observed for the western stock. Vertical resolution data of the reproductive layer thickness for both stocks showed improved reproductive conditions for eastern cod of ca. 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 during recent years Eastern Baltic cod progressively immigrated into the Arkona Basin. 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 recruitment of the eastern cod stock in this management area. However, this was only possible for relatively late spawning eastern cod and in years characterized by specific conditions, i.e. after summer inflows of saline water.

8. Present knowledge gaps

There is still a need for better understanding the role of P-E+R on salinity distribution and its variability on seasonal to inter-annual time scales. The surface salinity of the eastern Gotland Basin varied over the recent 4 decades (Fig. 4). In the 1970s, starting at relatively high values of about 7.5 gkg^{-1} decreasing until 2002 and then slightly increasing again 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 sea) and/or river runoff (Radtke et al. 2020). There is work to be done to better understand the development of the salinity stratification and its role for 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 salt water inflows. Even if these have been studied for decades, we can pose the question: do we really understand the process, can we predict MBIs? Forthcoming work need to explore the chain of processes which additionally to large barotropic inflows lead to an influx of highly saline and oxygenated water. As stated before, the frequency and intensity of large volume changes have not changed much during the last decades even if the frequency of MBIs has decreased considerable (Mohrholz et al., 2018). So, the question will rise: what differentiates MBIs from LVCs? Most probably, extended outflow periods prior to the inflows are of importance, not only to reduce the mean sea level of the Baltic Sea but also to build up a haline stratification in the Danish Straits. Furthermore, transport rates which are related to the frequencies of low-pressure systems passing over the Baltic Sea and the strength of the wind play a role as indicated by the higher relative frequency of cyclone counts for MBIs compared to LVCs. However, this topic requires further detailed analysis of the dynamics and the processes which set up the stratification in the Danish Straits before LVC/MBI events. 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 (Radtke et a. 2020). Both river runoff and the strength of barotropic inflow show a variation on a 30-year timescale, and both of them show a stable and plauisble phase relationship to be the driver of interdecadal salinty variations (Radkte et al. 2020).

Recently observed summer inflows of saline water masses from the North Sea and Kattegat area into the central Baltic Sea might result in a higher connectivity between the nursery areas of pelagic fish species west of their major spawning grounds and the spawning stocks, e.g. for Baltic cod and flounder (Ruzzante et al., 2006; Svedäng et al., 2007). Backward migration to the major spawning areas when the fish reach maturity can be expected and would properly help to increase the recruitment of these species. Unfortunately, detailed information about this process are presently not available. At the time, detailed studies on summer inflows and how they might changed over time are missing. There are also local processes which deserve further studies. Detailed assessments of the exchange between coastal areas including lagoons and open sea, and between sub-basins, the cold intermediate layer (CIL) and turbulent mixing are not available. To improve our knowledge of these processes, we need detailed and joint modelling 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 still few regular observations of it and the modelling exercises show large discrepancies between their results and observations.

9. Key messages

The long-term salinity dynamics is controlled by river runoff, net precipitation and the governing east-west wind conditions, i.e. the water mass exchange between North Sea and Baltic Sea. 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. The reason behind this is not clear. 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 Darss Sill.

The mid-term and short term (monthly/annual/decadal) salinity dynamics is much more complex with strong salinity variability also affecting temperature and oxygen distribution, especially in and below the permanent halocline (Fig. 2). Over recent decades, negative salinity trends appear at the surface At the same time temperature increases and oxygen decreases. The temperature trend (~0.4 °C/decade) is about the same as the air temperature trend over the Baltic Sea. The trend in oxygen is strongly related to the increasing temperatures (changing solubility and oxygen depletion rates) with maximum negative trends up to 1 ml/l/decade in the area of the halocline (Bornholm and Gotland Basin, Fig. 3). After the major saltwater inflow in December 2014, new research has been stimulated to revisit the barotropic water exchange between Kattegat and Baltic Sea. Salt water inflows can be understood as a subset of barotropic inflows which happen in response to a specific sequence of atmospheric circulation patterns and clustering of deep cyclones in space and time. The strength of the inflows and the amount of salt which is 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 important role in the development of the deep water salinity, but recent studies show that the frequency of major saltwater inflows did not change. So, the associated worsening of bottom oxygen conditions are caused by excessive nutrient loading and related oxygen consumption and maybe due to 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 becoming changing climatic conditions, the development of the salinity regime at regional scales may have various basic-specific features which might be diverse from corresponding trends in the main Baltic Sea. This fact will rise a high demand to carry out basin-specific studies to understand the becoming changes in the local salinity regime.

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Pictures BEAR Salinity dynamics

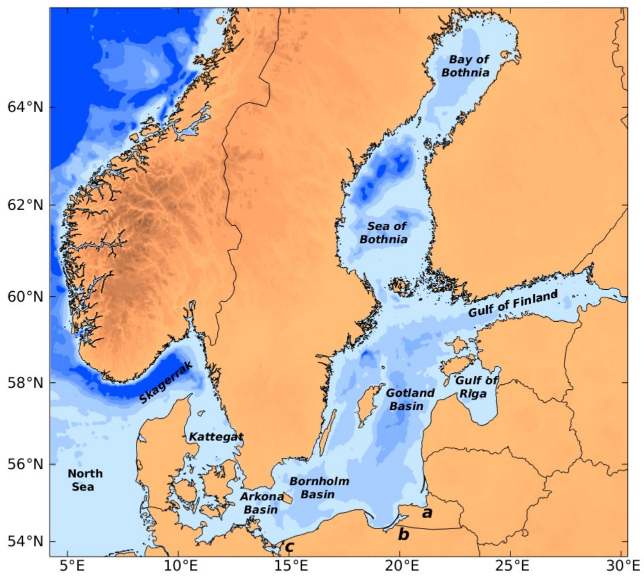

Fig. 1. Map of the Baltic Sea and its sub-basins. The Baltic Proper comprises the sub-basins Arkona, Bornholm and Gotland Basin. The Gulf of Bothnia comprises the Sea of Bothnia and the Bay of Bothnia. (a), (b) and (c) denote the Curonian, Vistula and Szczecin Lagoons.

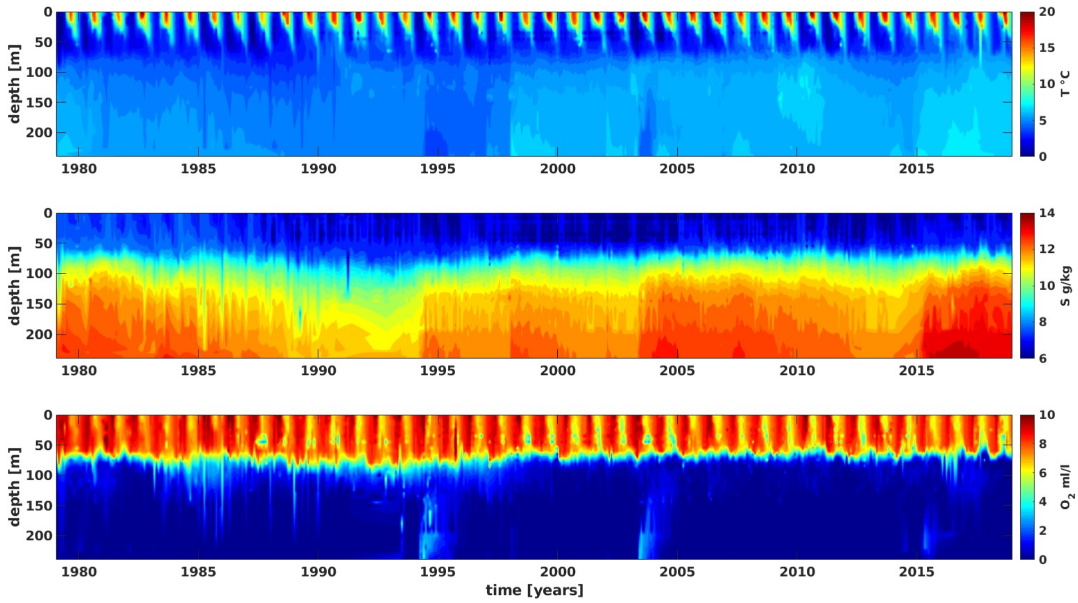

Fig. 2. Time series of temperature (top), salinity (middle) and oxygen (bottom) of ICES profiles of SD 28 (eastern Gotland Basin) for the period 1979-2018.

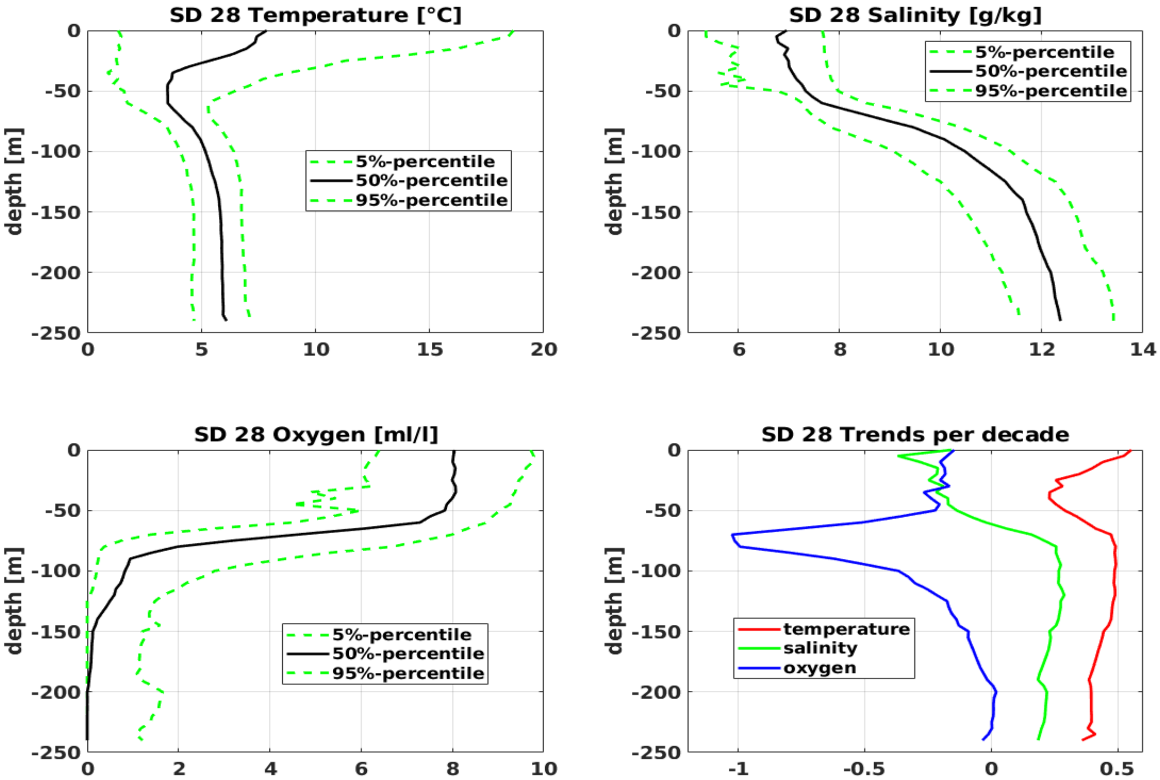

Fig. 3. Percentiles (5, 50 and 95%) of temperature, salinity and oxygen profiles for SD 28 (eastern Gotland Basin) for the period 1979-2018. Trends per decade of temperature, salinity and oxygen based on SD 28 temperature, salinity and oxygen profiles for the period 1979-2018 (right lower panel).

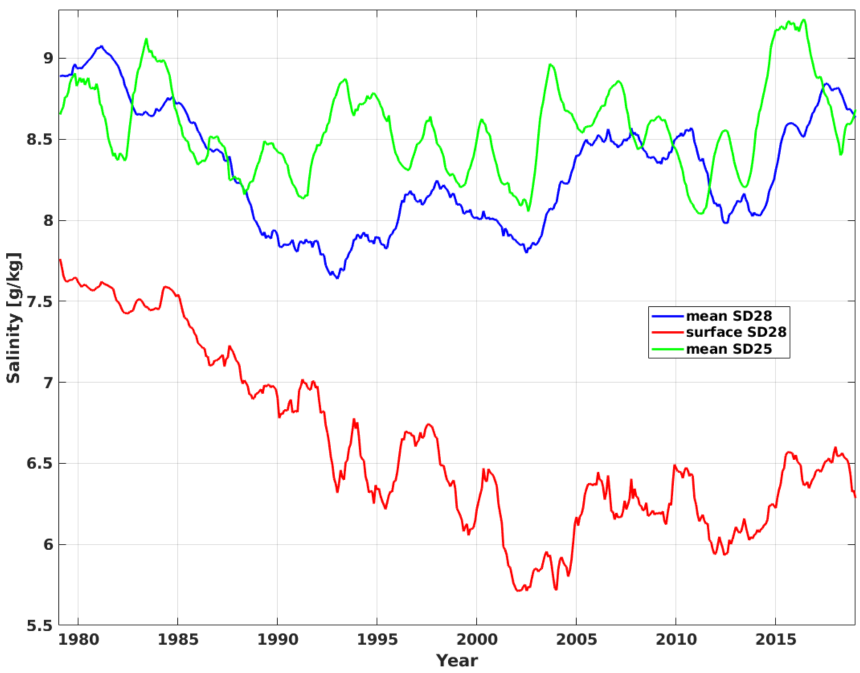

Fig. 4. Mean salinity of SD 28 (eastern Gotland Basin) (blue) and surface salinity of SD 28 (red). For comparision mean salinity of SD 25 (Bornholm Basin) (green) for the period 1979-2018. All series 12 months running means.

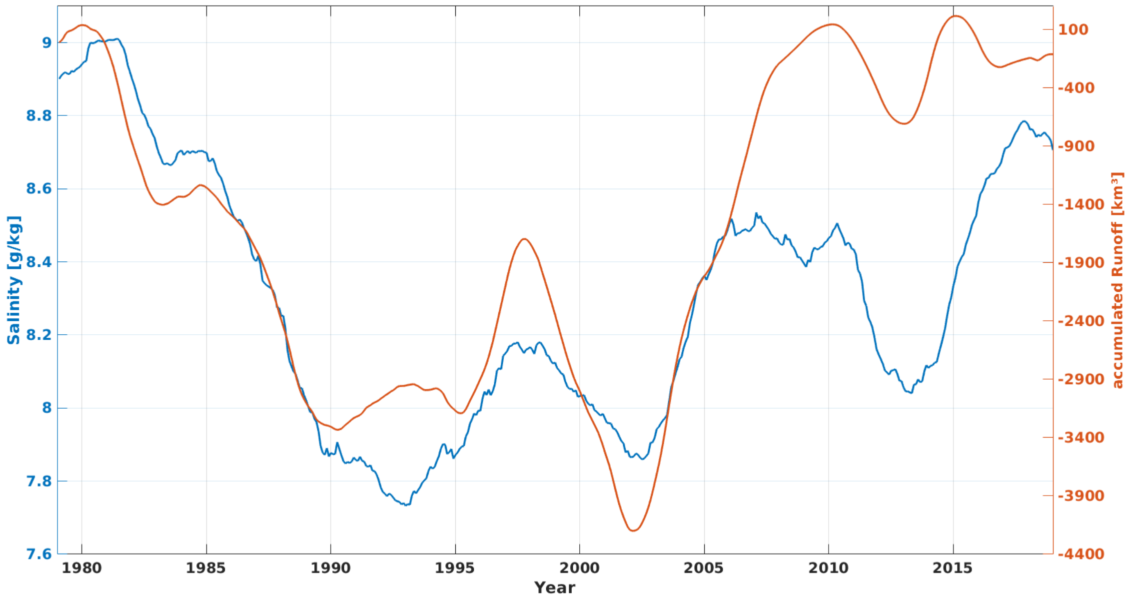

Fig. 5. Volume averaged salinity of SD28 for the period 1979 to 2018 and accumulated anomalies of runoff to the Baltic Sea (inverted). The correlation coefficient is 0.76.