Salinity dynamics of the Baltic Sea

– BEAR Report –

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Abstract

The salinity in the Baltic Sea is not only a topic of physical oceanography, but it also involves the complete water and energy cycle. It is also a primary factor (driver) controlling the ecosystems of the Baltic Sea. The salinity dynamics is controlled by net precipitation, river runoff and the water mass exchange with the North Sea with outflow of the Baltic Sea due to freshwater surplus and a compensating inflow of higher saline waters from the Kattegat in deeper layers, strongly controlled by the prevailing atmospheric forcing conditions. Since the Baltic Sea ecosystem has adapted to the present salinity regime, expected changes would exert enormous stress on marine fauna and flora with associated negative social-economic consequences for the Baltic Sea countries. However, the present understanding of salinity changes is still very limited, and future projections of the salinity evolution are rather uncertain. More detailed investigations on regional precipitation patterns (runoff), atmospheric variability (wind), -saline water inflows, the exchange between the sub-basins and turbulent mixing processes are still needed.

Since BACC II which has been published in 20154, collecting mostly research results until 2012, there have been new research on the salinity dynamics of the Baltic Sea stimulated by Baltic Earth. Especially, after the recent major Baltic inflow in December 2014 a number of new studies emerged. The research focused on key topics such as: the interrelation between decadal climate variability and salinity, the water mass exchange and major Baltic inflows 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.

1. Introduction

The salinity in the Baltic Sea is not a mere oceanographic topic but involves the complete water and energy cycle which have Baltic-specific features. Salinity is also an elementary factor controlling the ecosystem behavior of the Baltic Sea. The salinity dynamics is controlled by many factors: net precipitation, river runoff, surface outflow of Baltic fresh waters and the compensating deep inflow of higher saline waters from the Kattegat.

Furthermore, due to the expected increase in precipitation during the coming decades, ~~first~~ scenario studies indicate even a decrease in salinity of about -0.6~~2-3~~ g/kg in the ensemble mean -until the end of the century (Saraiva et al., 2019). Since the Baltic Sea ecosystem has adapted to the present salinity regime, expected changes would exert an enormous stress on marine fauna and flora with associated negative social-economic consequences for the Baltic Sea countries.

Even if the Baltic Sea physics has been investigated for a long time, our present understanding of salinity changes is still very limited. Not surprisingly, the future projections of the salinity evolution are rather uncertain. More detailed investigations on regional precipitation patterns and their relations to river runoff, atmospheric variability,~~;~~ wind forcing, the exchange between the sub-basins and turbulent mixing processes, are still needed. Furthermore, there is also a need for new climate projections simulations with improved atmospheric and oceanographic coupled model systems (Meier et al., 2019). Suggested general key research areas are the interrelation between decadal/climate variability and salinity, water mass exchange and major Baltic inflows. Do we understand the dynamics of the present-day salinity distribution, and can we predict MBIs?

In addition, detailed studies on the regional salinity distribution/variability and associated circulation patterns, including salinity fluxes between the coastal areas and the open sea and within the sub-basins, are needed. -Since BACCII, which was published in 20154, 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 MBI in December 2014, a number of new studies emerged on that. The research focused on key topics such as: the interrelation between decadal climate variability and salinity, the 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.

The paper is organized as follows. First, we summarize the knowledge which has been collected and summarized in BACC I and II books. After that, we asses recent publications and knowledge following the BACC-process after 2012. This part starts with the description of the atmospheric forcing driving the salinity dynamics followed by a~~n~~ detailed update of the knowledge of salinity dynamics. Further on, we study new features of salinity dynamics in regional scale, concerning the main basins in the Baltic Sea. Then 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 improve our understanding of the oxygen dynamics. Additionally, the salinity dynamics is also related to the environmental conditions of the marine ecosystem (eutrophication, fisheries, etc.) in Baltic Sea which is discussed, too. The paper ends with some conclusions and suggestions for 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, 2008, BACC II, 2015). We will summarize shortly here the earlier findings of salinity dynamics in order to set up the base of current understanding:

Salinity and saltwater inflows which were reported in BACC I include the following main findings:

- The mean salinity of the Baltic Sea decreased during the early twentieth 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 dynamic system. However, it is worth to notice that no long-term trend was found for salinity if the entire twentieth century is taken under investigation.
- Since the mid-1970s, the frequency and intensity of MBIs from the North Sea have decreased. However, according to later studies (Mohrholz, 2018) there is no trend on centennial time scale but ~~might be~~ a multi-decadal~~long-term~~ variability of MBIs. T~~and all~~

~~t~~he measurements before and after 1976 are not comparable due to changes in measurement sites~~ etc~~.

- Major inflows were absent between February 1983 and January 1993. During this low-salinity phase, the deep water of the eastern Gotland Basin was poorly ventilated, with oxygen depletion as a consequence. In the Gulf of Finland, an opposite development took place: the halocline vanished and the bottom oxygen conditions improved.

Salinity and saltwater inflows which were reported in BACC II include the following main findings: (the references, here, extend more-or-less until year 2012)

- Recent 2-3 decades are characterized by slightly lower than normal top-layer salinity, caused by higher accumulated river runoff, and by increased~~reduced~~ stratification strength and deep salinity (Liblik and Lips, 2019)~~, caused by increased mean zonal winds stress (probably only true until 2012)~~.

Kommentiert [m1]: So far this has not been shown

- Changes in water exchange and mixing events are also important depending on frequency of deep cyclones and their pathways over the Baltic Sea area. These will have an impact on the total salinity of the Baltic Sea and stratification conditions.
- In particular, MBIs, usually of barotropic origin, occur in favorable conditions during winter and spring when easterly winds are followed by several weeks of strong westerly winds. The~~se~~ occurrence of these two wind events back-to-back are not very common in the Baltic Sea. This keeps the 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 probable, occurred also before, but have not been observed.

3. Atmospheric forcing driving the salinity dynamics of the Baltic Sea (Piia, Andreas,...)

- large scale and regional scale atmospheric variability driving in- and outflows
- local/regional changes in atmospheric conditions

4. Update of the knowledge of salinity dynamics since 2012 (all)

Kommentiert [m2]: A sub-section on mixing is lacking, e.g. the new results by Holtermann et al. on lateral boundary mixing, by Holterman et al. on interior mixing after saltwater inflows and by Umlauf et al. on double diffusion.

4.1 Results from the 1st Baltic Earth Conference

The water exchange with the North Sea through the Danish Straits including major Baltic inflows is still a hot topic. There has been a revision of the definition of major Baltic inflows which are a part of Large Volume Changes (LVCs) or barotropic inflows. It has been shown that over recent decades no significant trend in barotropic inflows could be detected, contradicting the negative trend in MBIs. However, long-term observations of temperature and salinity (in a temporal scale of a few decades) revealed an increasing temperature trend and a decreasing trend in salinity at the surface, but an increasing trend in the deeper layers associated with an increasing stratification. Additionally, the atmospheric forcing responsible for major Baltic inflows has been investigated and related to barotropic inflows. The Atlantic Multidecadal Oscillation (AMO) could be associated with temperature variability of the Baltic Sea on long timescales. On shorter timescales the North Atlantic Oscillation (NAO) is one of the main drivers of temperature variation at the Baltic Sea surface, especially during winter. Furthermore, barotropic inflow characteristics have been investigated with respect to salinity. It could be demonstrated that for highly saline inflows specific atmospheric conditions are necessary, whereas river runoff only plays a minor role. The effect of rising sea level on barotropic inflows with respect to an enhanced salt flux has also been discussed. The effect of brine release on vertical mixing/convection has been investigated in a numerical model study. However, the brine release during sea ice formation of the very brackish northern areas is rather small, it is not strong enough to lead to effective deep water formation even in the weakly stratified northern areas of the Baltic Sea. The inter-sub-basin water exchange during MBI events has been studied by a numerical model with very high spatial and horizontal grid resolution. Especially, the salt flux downstream into the Baltic Proper, the Gulf of Finland and Gulf of Bothnia could be increased improving the salt deficit often found in coarser grid numerical model studies. The Slupsk Channel is a critical region of the central Baltic Sea as the water mass exchange between the Bornholm Basin and the eastern Gotland Basin as well as the Bay of Gdansk is strongly controlled by entrainment and vertical mixing. New measurements with high spatial resolution classify the Slupsk sill overflow as mixing hot spot for the eastward propagating saline deep water.

4.2 Development of the mean salinity (Volker, Kai, Andreas.,..)

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 ~~are~~ those seen in estuaries and fjords. The overall salt content of the Baltic Sea depends to a large extent on net precipitation and river discharge; with higher salinity during dry periods and lower salinity during wet periods. However, the salinity level is mainly governed by the variability in the water exchange between the North Sea and Baltic Sea (Winsor et al. 2001, 2003; Meier and Kauker 2003; Gustafsson and Omstedt 2009) which by itself is governed by the prevailing atmospheric conditions. Periods of westerly winds (NAO+ conditions) are accompanied by the advection of moist air from the Northeast Atlantic, and periods of easterly winds (NAO- and blocking or SCAND) are associated with dry air advected from eastern Europe. The mean salinity averaged over the Baltic Sea (Fig. mean salinity, BSIOM) shows a decline until 1993, then, with the MBI in 1993 an increase, and with the inflow in 2003 a jump in the mean salinity, strongly fluctuating and slightly decreasing until the end of 2018.

4.3 The cold intermediate layer (Irina)

As an inland sea, the Baltic has water masses of two principal origins, which constitute generally two-layered vertical stratification of estuarine type: with freshened upper layer, denser/saltier deep water of oceanic origin, and an inclined pycno/halocline between them. At the same time, large spatial scale of the sea, shallow and narrow outflow channels, severe mid-latitude wind climate make internal, inter-basin exchange of waters an influential factor for sea-scale salinity regime. One of the most obvious manifestations of water-exchange within the sea is annual formation of the Cold Intermediate Layer (CIL), present during the major part of a year. On the T,S-diagram of Fig. TS(a), based on IOW monitoring data for Gotland deep in May 2005 (blue) and 2006 (red), apart from the upper-layer freshened waters and deep saline waters, the water mass of the CIL is shown as a dense cloud of points with anomalously low temperature (close to and often below than the temperature of the density maximum, Tmd), and the salinity slightly larger than that of the upper layer. In contrast to the cold intermediate layers of other European inland seas - the Mediterranean or the Black sea – the Baltic CIL still keeps in secret even the basic questions: where its waters were formed, and which mechanisms are at work during its formation. It seems, however, obvious that the sea-scale salinity field plays an important role here, since influence of water temperature on the density is very small (and especially small – in the vicinity of the Tmd); this way, low water temperature can be used here as natural tracer of the exchange, driven by more influential factors.

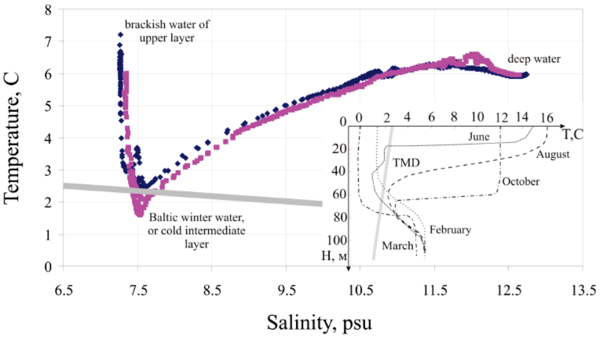
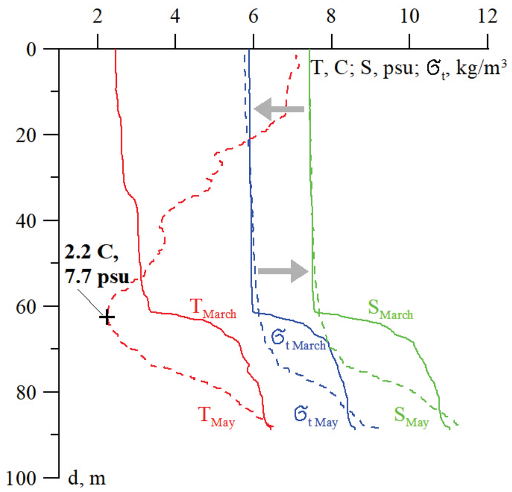


Fig. 2. Temperature-Salinity (TS) diagram derived using the IOW monitoring data for May of 2005 (blue) and 2006 (pink) at the Gotland deep. The Baltic Sea Cold Intermediate Layer (CIL) is identified. The inset shows the vertical temperature profiles for different months ((HH92), after Piechura with changes, the Gulf of Gdansk). TS-diagram shows three principal water masses of the Baltic sea as the most distant points of the diagram, whilst quasi-linear portions correspond to waters formed by their mixing (see also (Mamayev, 1975; Hagen and Feistel, 2007).

a)



b)

Fig. TS. a) from Chubarenko, Demchenko,2010; b) from (Chubarenko, Stepanova, 2018): Appearance of the CIL on vertical profiles of water temperature, salinity, and density anomaly in 2005 in central part of the Gdańsk Basin. Data: St.13, 4 March and 14 May 2005. Complicated structure of vertical temperature profiles in May illuminates advective origin of the cold intermediate layer. Note: the coldest (about 2.2–2.4 °C) waters in the depth range of 55–65 m in May have salinity higher than local salinity of the upper mixed layer in March.

The CIL in the Baltic, of the thickness of 20-50 m, is newly formed every year at the depth range of about 20-50 m, and over the entire Baltic Sea aquatory deeper than 60 m. However the depths of its upper and lower boundaries, vertical structure, water temperature are very variable, and only generally reflecting the past winter conditions. For example, it is shown that after the cold and severe winter the CIL is substantially thinner than after the mild winter, but has larger density gradients at its upper and lower boundary (i.e., stronger vertical density stratification), as well as larger heat deficit (i.e., larger “cold content”). Data analyses reveal highly inhomogeneous vertical thermal structure of the CIL waters (Chubarenko, Demchenko,2010; Stepanova et al., 2015), slightly larger salinity (plus 0.2-0.3 to the upper layer waters), presence of quasi-homogeneous and gradient sub-layers in the fields of salinity and density (Stepanova et al., 2015; Stepanova et al., 2015; Stepanova, 2017), which all highlight the advective origin of the CIL. Targeted field campaigns show vivid intrusion activity in intermediate layers in spring (April), when the CIL is becoming obvious in vertical thermohaline structure of the Baltic. Several field investigations (e.g., Eilola, 1997; Eilola, Stigebrandt, 1998; Zhurbas, Paka, 1999; Stipa, Vepsäläinen, 2002; Demchenko et al., 2011; Demchenko, Chubarenko, 2012; Chubarenko et al., 2017) mention for the same time period, that shallow spring thermocline appears in the Baltic Proper not via the direct solar heating of local waters but due to advection of relatively thin (4-5 m) eddy-structured surface lighter/fresher water from northern areas: these waters are protected by the density jump from mixing with colder underlying waters and are thus effectively heated. Such a coherency of sea-scale exchange events – activity of cold intrusions in intermediate layer and advective building of shallow spring thermocline near the surface – has raised a hypothesis of “spring release” in the Baltic Sea (Chubarenko, Stepanova, 2018), i.e., seasonal transfer from winter-time to summer-time vertical stratification, driven by longitudinal salinity gradient of estuarine nature within the upper (freshened) layer. It is suggested that the sea-scale exchange is driven by early-spring release of gravitational energy excess, which was maintained in winter time by vertical mixing: when mixing ceases, the 500-km long, 30 to 80 m thick vertically homogeneous layer with longitudinal salinity gradient relaxes to more gravitationally stable stratification (Chubarenko, Stepanova, 2018). This way, the cold waters of the upper mixed layer of south-western part of the Baltic Sea Proper in March, with their typical salinity of 7.4-7.8 (the Bornholm basin, eastern Arkona basin), are suggested to form the CIL in the Baltic Proper in summer. Satellite SST-data confirm that waters with temperature below 1.5 °C are present in the Arkona-Bornholm area in spring even under monthly averaging (large enough time scale is important for basin-wide effects): Fig. SST shows the multiyear location (occurrence) of the coldest waters in the Arkona-Bornholm area, estimated from monthly mean SST fields for March-April 2003-2019 (data: http://oceancolor.gsfc.nasa.gov).

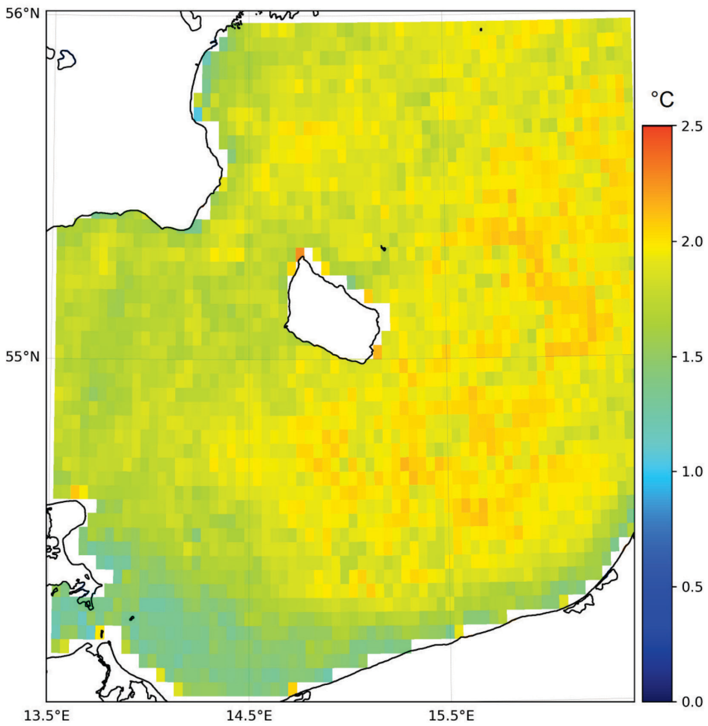


Fig. SST. Occurrence of the coldest waters (0-2.5 °C) in the Arkona-Bornholm area. Obtained on the base of the multiyear monthly averaged SST data over 2003-2019 (data: http://oceancolor.gsfc.nasa.gov).

Thus, the salinity regime in the Baltic Sea exhibits seasonal sea-scale changes, which call for further investigations. Next steps suggest, along with the targeted field campaigns, the analysis of SST data for probable source regions, and numerical modeling to disclose intermediate-water pathways and timing.

5. New knowledge of regional salinity dynamics

- LVCs/MBI Danish Straits, western Baltic Sea and Baltic Proper (Volker)

5.2 Salinity dynamics of Lagoons (Inga)

Baltic Sea Lagoons represent a complex and unique coastal environment which requires special attention in the context of climate change. 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, and usually geographically oriented parallel to the shore-line. Lagoons represent nearly 13% of the shoreline globally and around 5% in Europe (Lillebø et al., 2015). Some of the larger European lagoons (ex., Curonian Lagoon, Vistula Lagoon, Szczecin Lagoon) are in the Baltic Sea. This was due to the Baltic Sea's geomorphological processes and sea waters cyclonic hydrodynamics forming the sediment transport along the south-eastern coasts, and formed existence of accumulative form spit separated shallow lagoons from the open sea area. As it is known, also, the lagoons were formed by transporting continental sediments from larger rivers of the Baltic Sea catchment basin. The basic morphometric and hydrological characteristics of the lagoons are presented in Table 1.

The salinity of lagoons is closely related to water balance elements and climate change processes in the Baltic Sea region. All of these lagoons water balance elements (river runoff, sea salt waters intrusions, precipitation, evaporation, sea water entered), rise of air temperature, SST and sea level are changing and are expected to change in the future as direct or indirect consequences of global climate warming. The warming trend of the mean surface water temperature in the south-eastern lagoons of Baltic Sea (Curonian lagoon, Vistula Lagoon, and of Darβ–Zingst Bodden Chain) was 0.03 °C year^{-1} in the period 1961-2008 and about 0.05 °C year^{-1} after 1980 (Dailidiene et al. 2011). The Curonian Lagoon ST is projected to increase by 2–6°C by the year 2100 (Jakimavičius et al. 2017).

Water temperature and sea level rise which in turn leads to an increase in water salinity (due to inflow) are fundamental environmental descriptors that play a vital role in sustainability of lagoon ecosystems and environments.

The water exchange between lagoons and the Baltic Sea is governed by wind-induced differences in water level. For the future the sea level rise of the Baltic Sea is projected to rise, thus affecting the balance of water and salinity in the lagoons. The lagoon's water level is usually higher than that of the Baltic Sea, however, this difference in heights may have a downward trend due to rising sea levels. For example, in the Curonian Lagoon (CL) and in the Vistula Lagoon (VL) water level grew 18 cm, and the rate during the period between 1961 and 2008 was recorded for the Curonian and Vistula lagoons □4 mm year^{-1} (Dailidiene et al. 2011).

The Curonian Lagoon which located in the southeastern part of the Baltic Sea is the largest coastal shallow lagoon in Europe. The salinity distribution in the Curonian Lagoon is a result of the interaction with the atmosphere, freshwater runoff from the watershed and water exchange with the Baltic Sea through the narrow (300-600 m) Klaipeda Strait. The enclosed shallow Curonian Lagoon has a narrow connection to the Baltic Sea in the north and is exposed to the freshwater discharge of the Nemunas River in the central part. The Nemunas River is the dominant fresh water supplier for the Curonian Lagoon. The total run-off of rivers to the lagoon varies from 14 km^3 $year^{-1}$ to 33 km^3 $year^{-1}$ (Jakimavičius et al. 2018) and exhibits a strong seasonal pattern, peaking with snow melt during the flood season which happens depending on the duration of the cold season between February and April. The volume of fresh water discharge from the Nemunas River and other smaller rivers is on average about 22 km^3 year. The theoretical residence time of water in the Curonian Lagoon is about 80 days. The water salinity in the southern and central parts of the lagoon is up to 0.05 ‰ (g kg-1), directly influenced by river waters. While in the northern part it is oligohaline with irregular salinity fluctuations from 0 ‰ to 7.5 ‰ (g kg-1). Investigations of long-term annual mean salinity fluctuations proved that the water salinity in the northern part of the Curonian Lagoon is increasing. Also this is related to the anthropogenic factor, the dredging of the seaport. Salinity distribution and fluctuations are mostly linked to the meteorological conditions that determine the inflow of saline water from the Baltic Sea. For example, blowing in the north, north-east winds (3-5 m s-1) along the south-eastern Baltic Sea coast may lead to an inflow of sea saltwater waters into the lagoons. During upwelling sea water can reach the central Curonian Lagoon part up to 40 km from sea entrance (Fig. 5.2.1).

Climate change projections revealed an increase of the Curonian Lagoon water salinity which can be attributed to changes of water exchange through the Klaipėda Strait and the Nemunas inflow. The study uses three climate model outputs under four RCP (Representative Concentration Pathways) scenarios, four sea level rise scenarios and hydrological modelling in order to project the extent to which water balance components, salinity and temperature may change in the future (Jakimavičius et al. 2018). This study indicate changes of the lagoon water balance components, salinity and temperature are expected to be more significant in 2081–2100 than in 2016–2035. It was projected that in 2081–2100 the river inflow may change from 22.1 km3 to 15.9 km3, whereas inflow from the sea is expected to vary from 8.5 km3 to 11.0 km3, and the salinity in north part of CL will rise from 1.4 ‰ to 2.6 ‰.

Not only climate change, but also a great anthropogenic load (deepening of port area, construction of hydraulic equipment, river water regulation, intensive navigation and ect.) directly affects the balance of the lagoons, including changes in the salinity regime of their waters.

The Vistula Lagoon is the second largest lagoon in the Baltic Sea after the nearby Curonian Lagoon. Average salinity of the Vistula Lagoon is 3.5 ‰ (g kg-1), and it may vary from 0.5 ‰ (g kg-1) at the southern part and to up to 6.5 ‰ (g kg-1) at the Baltiysk Strait. 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 running coastal lake to an estuarine lagoon with predominant marine influence (Chubarenko et al. 2017). Usually, such areas are subject to multiple issues and problems related to sustainable management of shared areas, and the Vistula Lagoon is no exception. The most obvious concern are plans for a large-scale modification of the natural system via the construction of a second inlet to the lagoon at the Polish side (Rózyn´ski et al. 2018). Water

balance of the VL (Rózyn´ski et al. 2018): estimated that 17 km3 (80.2%) of water entered the lagoon through the Baltiysk Strait, riverine inflows amounted to 3.62 km3 (17.1%), atmospheric precipitation accounted for 0.5 km3 (2.4%), 0.65 km3 evaporation (3.1%), and groundwater inflows for 0.07 km3 (0.3%).

The Szczecin Lagoon (SL) is also one of the largest lagoons in Europe. The lagoon is shallow (average depth of 3.8 m), has a salinity between 1‰ (g kg-1) and 3 ‰ (g kg-1), and is connected with the Baltic Sea via three outlets (Friedland et al. 2019). The Szczecin Lagoon is located at the border between Germany and Poland and is divided into Large Lagoon (Wielki Zalew) and Small Lagoon (Kleines Haff). The zonation of Szczecin Lagoon is thereby quite comparable to Curonian Lagoon with a slow water renewal in the southern part (Umgiesser et al., 2016).

Future changes in climate system components may stronger effect on water salinity balance in the Baltic Sea coastal areas, such as lagoons. Coastal lagoons of Baltic Sea could be most vulnerable to direct impacts of future climate change projections. It was estimated that future climate change projections in the Baltic Sea region also indicate future regional differences, e.g., the warming over the northern region will be more pronounced than over the southern region, and river runoff is indicated to increase in the northern region and maybe even decrease in southern areas (Meier et al. 2014). These changes mean that geographical areas of the Baltic Sea, including coastal lagoons, will have different salinity and stratification in future compared to present climate. There is a need to develop sea water salinity observation and modeling strategies to support adaptive management under combined climate change and anthropogenic pressures.

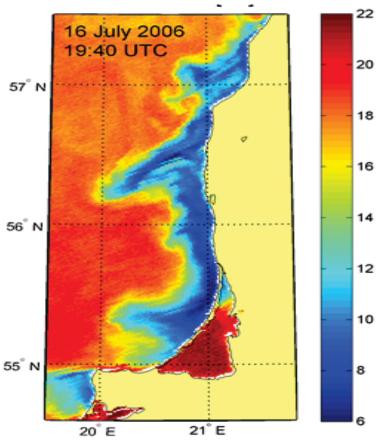


Fig.5.2.1 Upwelling phenomena indicated sea salt waters intrusions in the north part of the Curonian lagoon in South-eastern part of the Baltic Sea, MODIS data of SST (16 July 2006).

Table 5.2.1. Morphological and hydrological parameters of the Baltic Seal lagoons. (Data collected from: Schiewer, 2002; Schumann et al., 2006; Chubarenko and Margonski, 2008; Matciak et al. 2011, Dailidiene et al., 2011; Umgiesser et al. 2016; Jakimavičius et al. 2018; Friedland et al. 2019).

Parameter, dimension	Szczecin (Oder-) Lagoon	Neva Bay	Puck Lagoon	Darβ–Zingst Bodden Chain	Vistula Lagoon	Curonian Lagoon
Surface area [km^2]	687			197	838	1584
Volume [km^3]				0.4	2.3	6.3
Catchment area [km^2]	120 000			1 594	23 871	100 458
Mean depth [m]	~4	~4	~3.1	~2	~3	~4
Maximum depth [m] (depth of sea entrance navigation canals)	(~12)	12	9.4	3.9	5.2 (~8)	5.8 (~17)
Length [km]		21	15	66 (ferry way)	91	93
Width [km]				0.14-8.5	2-11	0.8 - 46
Average discharge from the rivers per year [km^3 year^{-1}]				~0.3	~4	~24
Inflow of marine water [km^3				~3	~17	~7

year^{-1}]						
Residence time (days)	75.5	4-5	1-3		40	80
Salinity range [PSU]	1-3	6.4-7		<0.5 -14.7	<0.5 - 6.5	<0.5 - 7.5
Mean salinity [PSU]				5.6	3.2	1.0

5.3 Salinity dynamics of the Gulf of Finland (Urmas, Taavi)

The Gulf of Finland is an elongated sub-basin of the Baltic Sea. Water budget in the gulf is mainly determined by the unrestricted water exchange with the Northern Baltic Proper in the west and river discharge, which is mainly concentrated in the eastern part. 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, respectively (Alenius et al., 1998, 2003). The seasonal thermocline vanishes every autumn-winter. Strong estuarine circulation reversal events (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 (Golubkov et al., 2017; Ylöstalo et al., 2016) to 6 g kg-1 in the western part (Pavelson et al., 1997). 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 circulation scheme (Andrejev et al., 2004). The westward flowing current along the northern coast (Rasmus et al., 2015) is changing its location across the gulf mainly due to wind forcing (Kikas and Lips, 2016; Liblik and Lips, 2017; Lips et al., 2016a; Stipa, 2004).

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 (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., 2017; 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 the deep layer (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 the 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 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 dependent on the occurrence of MBIs (Laine et al., 2007; Liblik et al., 2018; Liblik and Lips, 2011). If 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, 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 (Almén et al., 2017). Long-term records near the gulf at Utö revealed the sea surface salinity decrease from the early 1980s to mid-1990s (Laakso et al., 2018). 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). Salinity trend in the deep layer of the central gulf has been 0.04 g kg-1 in 1982-2016 (Liblik and Lips, 2019).

5.4 Salinity dynamics of the Gulf of Riga (Urmas, Taavi)

The Gulf of Riga is a seasonally stratified, semi-enclosed basin in the eastern Baltic 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). Water budget in the gulf is determined by 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 in the gulf. 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 a quite 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 above the halocline during the stagnation period until the mid-1990s (Raudsepp, 2001).

Transport of the 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). 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 the 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 entering of the sub-surface warmer, saltier, and oxygen-rich buoyant patches from the Irbe Strait into the gulf intermediate layer in summer. 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 the Gulf of Bothnia (Kai)

The Gulf of Bothnia is an imbedded semi-enclosed Baltic Sea basin where the hydrography is quite different from that in the other parts of the Baltic Sea. This is because sills and archipelagos in the southern section largely isolate the basin from the Gotland Sea. The sill between the Åland Sea and the Baltic proper prevents the northward propagation of the 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 (Kullenberg, 1981, Omstedt et al., 2004).

In the Gulf of Bothnia the salinity stratification is weak. In the Åland Sea the surface salinity is 5.25–6.25 ‰ whereas at the depth of 200 meters the salinity varies between 7 and 7.75 ‰. 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 Gotland Basin, 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.

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

The salinity stratification, even in the Bothnia Sea, is relatively weak and overall oxygen conditions have remained relative good, not to mention some specific coastal areas. To be accurate, the oxygen conditions in the deepest layers of 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 near future (Raateoja, 2012).~~,~~ For consistent hypoxic events to emerge, the climate of the northern hemisphere would have to force profound changes in the hydrographic regime of the BS.~~,~~ As the emergence of hypoxic events does not seem likely in the near 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 with regard to eutrophication.

Kommentiert [m3]: The fate of eutrophication is very much governed by the external nutrient load scenarios. For instance, under BSAP the environmental conditions of the GoF will very likely considerably be improved.

6. Climate variability and change – impact on salinity dynamics (all, choose your favorite topic)

6.1 Increasing temperature and heat content of the Baltic Sea

6.2 Changes in circulation and water exchange (MBIs, LVCs, etc).

6.3 Change of stratification from Observations (ICES/HELCOM or other data sources)

Thanks to hydrographic measurements campaigns, especially stimulated by the recent major Baltic inflow in December 2014 the hydrographic data base has increased tremendously.

6.4 The role of precipitation and river runoff

~~For the period under consideration there is no trend in runoff to the Baltic Sea. However we see an decreasing surface salinity and increasing salinity in and within the halocline especially in the eastern Gotland Basin.~~River runoff and net precipitation (precipitation minus evaporation) over the sea surface are dominant drivers of 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 (REF). Net precipitation amounts to about 10% of the total river runoff (e.g., REF, Meier and Döscher, 2002). For the period 1850-2008, the total river runoff from the Baltic Sea catchment area reconstructed from observations (Hansson et al., 2011a;

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., 2018b). 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). 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, 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 caused by AMO is still unknown.

Due to the projected increased freshwater supply from the catchment area by about 1 to 21% at the end of the century depending on the climate model, surface and bottom salinities are projected to decrease by about 0.6 g kg^{-1} in the ensemble mean with a large spread among the ensemble members (Saraiva et al., 2019b). Assuming an unchanged saltwater inflow frequency, a reduced overall salinity would cause a reduced stratification between surface and deep layer in the Baltic Sea causing an improved ventilation of the bottom layer and in some sub-basins such as the Gulf of Finland even an increase in bottom oxygen concentration (Meier et al., 2011).

6.5 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 (Trenberth et al. 2007). From AR5, the global mean sea level (GMSL) rise is about 1.2 mm per year 1930-1992, 3.2 mm per year for the period 1993-2015 and 4.4 mm/ per year for the period 2010-2015.

Hordoir et al. (2017) 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. (2017) 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). Instead, Arneborg (2016) proposed an alternative theory. 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.

~~Hodoir et al. studied the influence of sea level rise on the dynamics of salt inflows in the Baltic Sea by a suit of idealized model experiments specifying different degrees of sea level rise. Meier et al. 2016 investigated accelerated future global mean sea level rise on hypoxia of the Baltic Sea. Both model studies are idealized sensitivity experiments wit added time-independent sea level anomalies instead of transient simulations with continuously rising sea level as presented here.~~
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). Salinity and the ventilation of the deep water with oxygen are important drivers of the Baltic Sea ecosystem functioning and biodiversity (Vuorinen et al., 2015).

7. Oxygen conditions and biogeochemical implications (Markus and other volunteers)

The O2 conditions in the Baltic Sea are the result of physical transport of O2 and consumption of O2 by biogeochemical processes. Owing to the positive freshwater budget and the bathymetry of the Baltic Sea, a strong salinity gradient generates a permanent density stratification (pycnocline) that inhibits the vertical exchange of O2 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 O2 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. Matthäus and Franck (1992) used an intensity index to classify the inflow events during the last century (Fig. 18.6). During longer periods without a sufficient supply of O2 to the deep water, the continuous consumption of O2 by decomposition of organic matter results in O2 depletion and eventually in the development of anoxic conditions. Thus, the Baltic Sea is vulnerable to hypoxia and anoxia due to its hydrography (Conley et al. 2009a). The most northern parts of the Baltic Sea, the Bothnian Sea and Bothnian Bay, are characterised 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.

7.1 Oxygen Depletion and H2S Formation

Current process understanding: The main reason for O2 demand in sea water is the mineralisation of organic matter. This is an oxidation process performed by heterotrophic organisms that use the chemical energy stored in organic matter and thus reverse chemically the primary production process (see Box 18.2). A large fraction of the organic matter produced in the euphotic zone is sinking into deeper water layers, and by mineralisation, inorganic nutrients and CO_2 are again released. In addition to vertical transport, a considerable lateral transport of organic matter, produced in shallower areas, contributes to the C flux into the deep basins of the Baltic Sea and intensifies the mineralization process (Emeis et al. 2000; Hille et al. 2006; Schneider et al.2010).

Past changes: Eutrophication is considered the main cause of low O2 concentrations in the deep water of the present-day Baltic Sea (Larsson et al., 1985; Conley et al., 2009b, Carstensen et al., 2014; Meier et al., 2018b). The observed deep-water O_2 conditions during the last 100 years (Fig. 18.7) show that the occurrence of H_2S became much more frequent during recent decades. The increased availability of organic C due to eutrophication required more electron acceptors, and therefore, the depletion of O_2 and formation of H_2S were accelerated. Strong eutrophication started in the 1960s and peaked in the 1980s (Elmgren 2001; Gustafsson et al. 2012). In combination with a long-lasting stagnation period from 1983~~76~~ to 1993 (Fig. 18.6) without any significant dense inflows from the North Sea, eutrophication caused high concentrations of H2S in the deep water of the Gotland Basin. Other locations such as the Landsort Deep, however, showed an increase in O2 concentration. In this case, the missing inflow events weakened the stratification due to decreasing salinity and thus enhanced the vertical O_2 flux. Similarly, in the Gotland Basin, the decreasing stratification caused a deepening of the permanent halocline (Diekmann and Möllmann 2010), thus exposing larger bottom areas to ventilated surface waters, while H_2S concentrations in bottom waters below the ventilation depth increased (Fig. 18.7). The shrinking of the hypoxic area during long-lasting stagnation periods is illustrated in Fig. 18.8. It shows that the hypoxic area was much smaller at the end of the 1983~~76~~–1993 stagnation period than in 2006 after some recent inflows (Conley et al. 2002, 2009a; Savchuk 2010).

Kommentiert [m4]: Rephrase?

-Despite the decrease of riverborne nutrient loads after the 1980s, recently observed oxygen consumption rates are higher than ever observed, limiting the impact of natural ventilation by oxygen-enriched saltwater intrusions in the open Baltic Sea (Meier et al., 2018a).

In the Baltic Sea, hypoxia has expanded considerably since the first oxygen measurements became available in 1898. In 2016, the annual maximum extent of hypoxia covered an area of about 70,000 km^2, comparable with the size of Ireland, whereas 150 years ago hypoxia was presumably not existent or at least very small (Carstensen et al., 2011; Meier et al., 2018b). Hypoxia was mainly caused by accumulation of increasing riverborne nutrient loads and atmospheric deposition (Savchuk, 2010; 2018). The impacts of other drivers like observed warming and eustatic sea level rise were comparatively smaller but still important (Carstensen et al., 2011; Meier et al., 2018b). Hence, also halocline variations had an impact on hypoxia (Väli et al., 2013). Although in some coastal regions, as a consequence of implemented abatements, improved oxygen conditions have been observed, persistent and seasonal hypoxia remains a large problem for many coastal systems (Conley et al., 2011).

Future changes:

Projected warming and global mean sea level rise may reinforce eutrophication and oxygen depletion in the Baltic Sea by reducing air-sea fluxes and vertical transports of oxygen in the water column, intensifying internal nutrient cycling, and increasing river-borne nutrient loads due to increased river runoff (Meier et al., 2011; 2012a; 2012b). However, the response of deep-water oxygen conditions to changing climate will mainly depend on the nutrient load scenario (Saraiva et al., 2019a; 2019b). In the case of high (low) nutrient loads, the impact of the changing climate would be considerable (negligible). Scenario simulations suggest that the complete implementation of the Baltic Sea Action Plan (BSAP) resulting in required load reductions will lead to a significantly improved ecosystem state of the Baltic Sea irrespective of the driving global climate model (Saraiva et al., 2019b) and regional coupled climate-environmental model (Meier et al., 2018c).

For the end of the century (2069-2098), hypoxic area is projected to change only slightly in the ensemble mean under reference (-14 … -5%) and high (-2 … +5%) nutrient load scenarios compared to the period 1976-2005 (Saraiva et al., 2019b). In the reference scenario, nutrient loads represent the average loads of the period 2010-2012. The high or worst case scenario assumes changes caused by a ‘fossil-fuelled development’ scenario coupled to increasing river runoff (Saraiva et al., 2019a). Changes in nitrogen and phosphorus loads were calculated from the regional assumptions, e.g., on population growth, changes in agricultural practices such as land and fertilizer use and expansion of sewage water treatment plants (Zandersen et al., 2019). Under the BSAP scenario, hypoxic area will at the end of the century be reduced by 50 to 60% in the ensemble mean compared to 1976-2005 (Saraiva et al., 2019a).

For the first time, recently uncertainties in projections of the Baltic Sea ecosystem have systematically been assessed (Meier et al., 2018c; 2019). One of the identified larger sources of uncertainty are caused by biases of global and regional climate models, in particular, with respect to GMSL rise and regional water cycling (Meier et al., 2019). The mechanism behind the correlation between large-scale meteorological conditions in the different climate periods and O_2 conditions in the Baltic Sea is not well understood and subject to ongoing research.

8. The impact of salinity dynamics on the environmental conditions of the marine ecosystem (??, volunteers?)

- salinity and the development of the main fish stocks

Bauer et al. 2019

9. Knowledge gaps and outlook (all)

- monitoring of sea surface salinity by satellites (e.g. SMOS)
- monitoring of volume changes and mass by GRACE, Aviso+

10. Conclusions and key messages (all)

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Diverse texts taken from somewhere (might be useful)

The Gotland Deep (the deepest part of the eastern Gotland Basin, Fig. 7.1) 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 only, are only 2 % different to changes calculated based on data from all sub-basins (Winsor et al. 2001). Observations (Fig. 7.4) reveal low-salinity period above the halocline starting in the 1980s. Fresher periods also occurred in the 1900s and 1930s and to a less extent in the 1960s. Salinity and stratification of the deep layers are highly affected by the occurrence of MBIs of North Sea water. These occur when high pressure over the Baltic Sea region with easterly winds is followed by several weeks of strongwesterly winds (e.g. Lehmann et al. 2002; Matthäus et al. 2008; Leppäranta and Myrberg. 2009). During the history of observations since the 1900s, the strongest inflow took place in November–December 1951 (e.g. Madsen and Højerslev 2009; see the high bottom salinities in Fig. 7.4). During the peak inflow, the difference in sea level between Gedser and Hornbaek (i.e. between the northern and southern ends of the Danish straits) was up to 1.5 m and the normal saline stratification in the Kattegat and the strait area broke down for several weeks. A MBI of comparable magnitude occurred in December 2014. On average, new high-saline water reaches the deep layers of the Gotland Basin with a delay of up to a year (e.g. Kõuts and Omstedt 1993; Matthäus et al. 2008), as can be seen also in Fig. 7.4. The inflow during winter 1976/1977 was followed by an exceptionally long stagnation period, when the strength of the saline stratification (bottom to surface salinity difference) decreased by about one and a half times, before the next inflow in 1993. In some areas, such as the Gulf of Finland, the halocline effectively disappeared. An extensive stagnation period also occurred in the 1920s and 1930s, after the very strong inflow in winter 1921/1922, coinciding with the shift from a wet period to a dry period over the Baltic Sea basin. Based on water age calculation, Meier (2005) identified a stagnation period of more than eight years also in the 1950s/1960s. Since 1994, when stratification strength returned to the near-normal levels of the 1960s and 1970s, stagnation in terms of oxygen deficiency of the near-bottom waters continued (Conley et al. 2009, see also Chap. 18). In addition to smaller inflows, a series of larger inflows has also occurred since then. In contrast to the usual barotropic inflows (vertically uniform transport over the entrance sills) that occur in winter and spring and advect relatively cold water with high oxygen content into the Baltic Sea, the recent large inflows in the summers of 1997, 2002, 2003 (Feistel et al. 2006) and 2006 were of a two-layer (baroclinic) type that transported high-saline, but warm and low-oxygen water to the deep layers of the Baltic Sea. Thus, warm water inflows, whether baroclinic or barotropic, transport less oxygen to the Baltic Sea than cold water inflows, and higher temperatures increase the rate of oxygen consumption (through organic matter mineralisation) in the deep water and increase production of hydrogen sulphide (Matthäus 2006). Inflow activity is very clear in the daily temperature records for the deep layers in the Gotland Deep (Fig. 7.5). The low temperatures apparent during 2003 reflect the normal barotropic inflow in winter 2002/2003, described in many papers (e.g.Matthäus et al. 2008; Leppäranta and Myrberg 2009). Changing stratification strength also has a feedback to mixing processes. For example, Osiński et al. (2010) found that the major inflow in winter 2002/2003 increased the value of the first baroclinic Rossby radius of deformation (which determines the size of mesoscale eddies) in the southern Baltic Sea from about 4 km (in the pre-inflow period) to more than 9 km.

At the sub-regional scale, many aspects of the change in salinity and stratification are important in the context of ecological status and environmental and climatic impacts. When saline waters enter the Baltic Sea, the halocline is lifted up and this signal is dynamically transferred to the downstream basins (Meier 2007). Upstream from the Gotland Deep, in the south-western Baltic Sea, the variations in deep-water properties are generally of higher amplitude; downstream along pathways of deep-water advection they are damped due to a wide range of mixing processes (e.g. Reissmann et al. 2009). In the Bornholm Basin, deep temperature observations reveal waters of warm and cold inflows (Mohrholz et al. 2006) that can be later traced in the Gotland Deep. Bottom-salinity anomalies in the Bornholm Basin during 1961–2000 (Neumann and Schernewski 2008) −1 −1range from −1.8 g kg (1982) to 2.0 g kg (1994), with no significant trend although a recent slight salinity increase
could be seen. In the Lithuanian part of the Baltic Proper deep-water area, Dailidiené and Davuliene (2008) reported a strengthening of stratification for the period 1984–2005: decreased surface salinity and increased deep-water salinity. In the Gulf of Finland, a sub-region with a free connection to the Baltic Proper and the highest freshwater discharge per unit sea volume, changes in salinity and stratification generally follow those of the Baltic Proper, but are not fully synchronous

(e.g. Zorita and Laine 2000). On the basis of monitoring data for the period 1965–2000, Laine et al. (2007) found a continuous decrease in salinity and density stratification until the early 1990s, after which there was a slight increase. Based on independent data for 1987–2008, Liblik and Lips (2011) found that the deep salinities in summer increased after the 1993 major inflow by about −12 g kg . Despite the increased mean stratification strength and more frequent occurrence of hypoxia events (see Chap. 18), at the annual scale ventilation of deep waters is still effective and the annual mean oxygen concentrations remain higher than during the 1960s and 1970s (Laine et al. 2007). This can be explained by decreased sea-ice cover (see Chap. 8), which favours wind mixing (Vermaat and Bouwer 2009) and by stronger south-westerly winds in winter that cause stratification collapse events, due to wind straining effects on estuarine gradients (Elken et al. 2014). Reconstructing annual mean salinities since 1500 (Hansson and Gustafsson 2011) indicates that salinity has −1slowly increased by 0.5 g kg since 1500, peaking in the mid-eighteenth century. Present salinity values are nearly as high as reconstructed for the earlier maximum salinity period. Historically, there have been several fresher periods when the mean salinity of the Baltic Sea decreased from a −1 −1maximum of about 7.8 g kg to about 6.5 g kg . Hansson and Gustafsson (2011) also found a negative correlation between oxygen content and salinity, indicating that the major, upper, part of the water column was more efficiently ventilated when the Baltic Sea was in a fresher state.