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Ventilation of the Northern Baltic Sea

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Abstract. The Baltic Sea is a semi-enclosed, brackish water sea in northern Europe. The deep basins of the central Baltic Sea regularly show hypoxic conditions. In contrast, the northern parts of the Baltic Sea, the Bothnian Sea and Bay, are well oxygenated. Lateral inflows or a ventilation due to convection are possible mechanisms for high oxygen concentrations in the deep water of the northern Baltic Sea.

Owing to the high latitudes of the northern Baltic, this region is regularly covered by sea ice during the winter season. In March 2017, the RV *Maria S. Merian* was for two days in the Bothnian Bay collecting ice core samples, brine, and CTD profiles. The bulk sea ice salinity was on average $0.6\mathrm{g\,kg^{-1}}$ and in brine samples, a salinity of $11.5\mathrm{g\,kg^{-1}}$ and $17.8\mathrm{g\,kg^{-1}}$ have been measured. At one station, the CTD profiles indicated a recent ventilation event of the deep water. A water mass analysis showed that the ventilation is most probably due to mixing of Bothnian Sea and Bothnian Bay surface water which results in sufficient dense water able to replace older bottom water. However, the high salinity of brine provides the potential for forming dense bottom water masses as well.

1 Introduction

The Baltic Sea is a semi-enclosed marginal sea in northern Europe with a positive fresh water budget (e.g., Lass and Matthäus, 2008). Owing to its hydrographic conditions, an estuarine-like circulation is established and a strong and permanent vertical density stratification occurs. These hydrographic conditions set the prerequisites for vulnerability to hypoxia and anoxia below the pycnocline. In general, a ventilation is only possible by lateral intrusions of oxygenated water of a sufficiently high density which allows this water to enter depths below the pycnocline. Indeed, the modern Baltic Sea shows wide areas of hypoxia in its central part. However, the northern part of the Baltic Sea, the Bothnian Sea and Bothnian Bay, are characterized by well oxygenated bottom water although in recent years a decreasing oxygen concentration was reported (Raateoja, 2013).

Marmefelt and Omstedt (1993) investigate processes for deep water renewal in the northern Baltic Sea and concluded that inflows of dense water are the main process. In contrast to major Baltic inflows for the central Baltic Sea, those inflows into the Bothnian Sea and Bothnian Bay originate from surface water of the Aland Sea and Northern Quark (Fig. 1), respectively. Therefore, this inflowing water is saturated with oxygen and these events may occur more often than major Baltic inflows. Other possible processes, thermal and haline convection, have been assessed as highly unlikely. However, Marmefelt and Omstedt (1993) also notice that more observations from the Bothnian Bay are needed during winter time.

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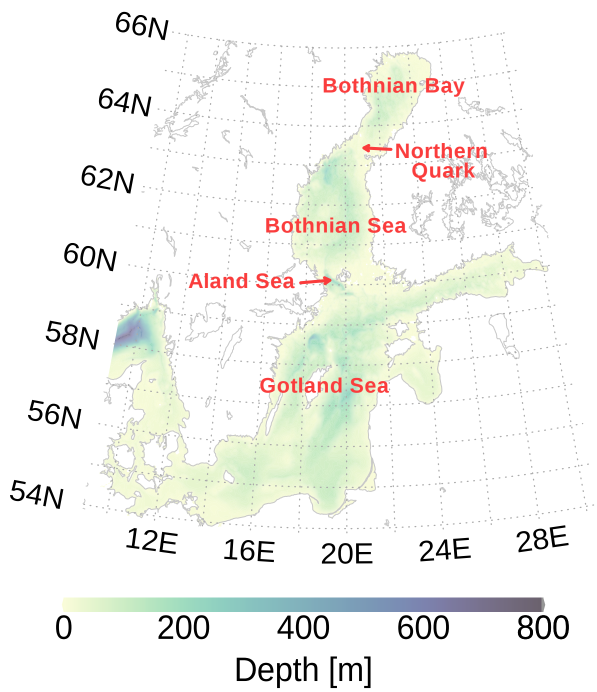

Figure 1. Bathymetry of the Baltic Sea showing names of different geographic regions we will use in the text. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).

Haline convection is initiated by brine rejection during the sea ice season. It is an usual phenomenon in arctic and subarctic regions. Dense and saline water masses are generated at hot spots of sea ice production, the polynyas. But also melting sea ice can produce considerable salt fluxes into the ocean (Peterson, 2018). The general idea is, that dense water is generated at the shelf and then a gravity driven flow can reach deeper regions of the ocean (Aagaard et al., 1981; Skogseth et al., 2008). However, owing to the rough weather conditions, experimental studies are sparse.

Owing to the low salinity, sea ice in the northern Baltic Sea shows a considerably lower bulk salinity compared to sea ice in the arctic ocean. Usually, values less than $1\,\mathrm{g\,kg^{-1}}$ have been observed (e.g., Meiners et al., 2002; Granskog et al., 2005). Therefore, the brine volume in Baltic Sea ice is smaller than in arctic sea ice, however, brine salinity is comparable (Assur, 1958).

In this study, we will present data from an expedition in the sea ice covered Bothnian Bay, the most northern basin of the Baltic Sea (Fig. 1), in March 2017. Samples from sea ice , brine, and water column profiles have been taken and analyzed. The aim of this study is to identify relevant processes ventilating the deep water of the Bothnian Bay.

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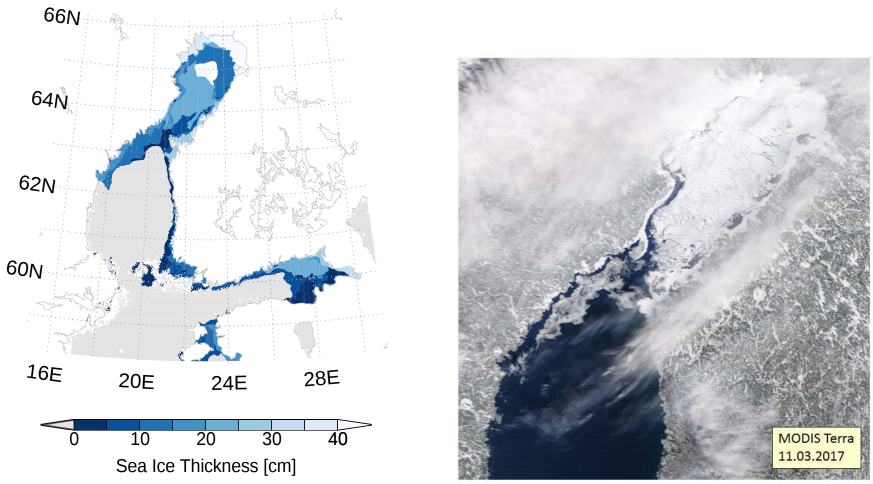

(a) (b)

Figure 2. Sea ice thickness (a) at March 12th 2017 in the Bothnian Sea and the Bothnian Bay. Data are based on the Finnish Meteorological Institutes ice charts and freely distributed by the Copernicus Marine Environment Monitoring Service (marine.copernicus.eu). Sea ice coverage (b), quasi true color image derived from MODIS at March 11th 2017. The map in (a) was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/)

2 Methods

The Baltic Sea ice season 2016-2017 was mild with a maximum ice extent of 80,000km^2 reached at February 12th (Baltic Icebreaking Management, 2017). Sea ice samples and water samples in the northern Baltic Sea, the Bothnian Bay and the Bothnian Sea, were taken during the expedition MSM62 with RV *Maria S. Merian* between 12th and 13th March 2017. In this time, the Bothnian Bay was well covered by sea ice (Fig. 2). For sea ice sampling, the RV sailed into the ice cover until it was surrounded by fast ice. In a distance of about 50 m from the RV, ice core samples were taken. Nearby of the ice core stations, shipborne CDT measurements were taken. For this purpose, the RV steamed a short distance to be freed from surrounding sea ice and the CTD probe could be lowered undisturbed. Names and locations of stations are shown in Fig.3.

2.1 Ice core sampling

With the aid of an ice corer, three to four sea ice cores were taken at each station. The length of the cores varied from 0.3 to 0.6 m. Obvious snow and loose parts were removed from the surface. In addition, holes approximately half the depth of the ice thickness were drilled to collect brine. Brine could be collected at two stations (stat. 8 and 10, Fig. 3).

Onboard, the ice cores were cut into two or three segments depending on the total length and structure of the ice core. Snow was removed from the ice fragments and then the ice was melted for further analysis. After salinity estimations, the melt water

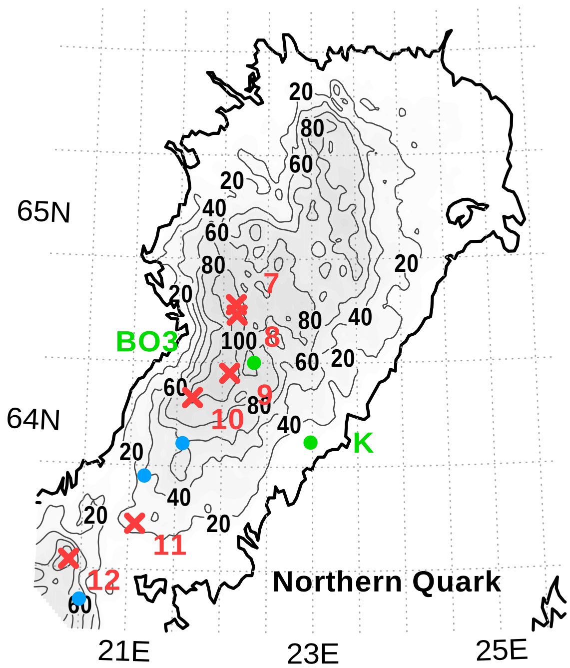

Figure 3. Locations of stations in the Bothnian Bay (stations 7 to 10), the Northern Quark (station 11), and the Bothnian Sea (station 12). Stations 7, 11, and 12 were CTD only stations. At stations 8, 9, and 10 sea ice and brine samples were taken. Nearby stations 9 and 10 also a CTD cast were performed. At stations BO3 and K (green dots), data from the HELCOM monitoring program are available. Blue dots refer to stations used in the discussion section. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).

was filtered and samples were prepared for analysis of yellow substances. Salinity was measured with a hand-held CTD (see section 2.2). In addition, selected salinity samples were measured with a salinometer. We used a Guildline's Autosal 8400B Laboratory Salinometer. It is the recognized industry standard instrument for measuring salinity in the laboratory. The Autosal employs an unique continuous flow system, where the sample water is drawn under low air pressure from the original sample bottle. A high stability temperature control bath and heat exchanger maintain this sample at a precisely defined temperature during analysis, avoiding the need for temperature compensation. The accuracy is better than 0.002 Equivalent Practical Salinity Units (PSU).

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2.2 Water column sampling

A CTD-system "SBE 911plus" (SEABIRD-ELECTRONICS) was used to measure pressure, temperature, conductivity, oxygen, fluorescence chlorophyll, back-scattering turbidity, and CDOM (colored dissolved organic matter, fluorescence method 370/460nm ex/em). For temperature, conductivity, and oxygen, two sensors were installed to ensure a high standard of data quality. A benthos altimeter delivered the bottom distance. Additionally, the CTD-probe was equipped with a SBE 32 water sampler with 13 free flow bottles of $5\mathrm{dm}^3$ volume.

The CTD was always put for at least 3 minutes at $10\mathrm{m}$ depth into the water before the cast started in order to remove air bubbles from the rosette and the pumping system. The CTD was lowered with 0.3 to $0.5\mathrm{m\,s}^{-1}$. Water bottles were closed during downcast automatically; only closing of the surface-bottle was triggered during upcast by hand.

We re-calibrated each oxygen profile with the assumption that the upper $5\mathrm{m}$ are well mixed and saturated with oxygen. That is, a small offset has been applied to all oxygen profiles.

After sea ice coring, a hand-held CTD was deployed through the borehole to measure the water column directly below the sea ice. For these measurements, a CTD48M by Sea & Sun Technology was used. The CTD48M is a very small multi-parameter probe for precise online measurements. Data is stored internally and can be downloaded after the mission. Owing to the low weight of 1.2 kg and the small housing diameter of 48mm, the probe is well suited for a deployment in a borehole.

The probe was equipped with a pressure, temperature, and conductivity sensor. The pressure transducer is a piezo-resistive full bridge. For temperature measurements, a platinum resistor with nominal 100 Ohm resistance at $0^{\mathrm{o}}\mathrm{C}$ (PT100) is used. Conductivity is measured by a cell which consists of a quartz glass cylinder with 7 platinum coated ring electrodes.

All shown quantities, like conservative temperature, absolute salinity, freezing temperature, density etc., have been computed following the TOES–10 manual (ICO et al., 2010) from measured in situ data.

2.3 Seawater optics

For the determination of the spectral absorption of dissolved organic substances (CDOM, yellow substances), seawater was filtered under low vacuum through Whatman GF/F glass fiber filters (pore size approximately 0.7µm). The filtered water was measured in a $10\mathrm{cm}$ cuvette using a dual-beam Perkin Elmer Lambda 2 instrument in the wavelength range between 300 and 750nm with increments of $1\mathrm{nm}$. Milli-Q water was the reference. Comparisons between Whatman GF/F and membrane filters with a pore size of 0.2$\mathrm{µm}$ did not deliver significant differences for the area of investigation.

The spectral absorption coefficients ay(λ) were calculated according to Kirk (1994):

$$ay(\lambda) = 2.3026(A(\lambda) - A(720\mathrm{nm})/l,$$

where A(λ) is the spectrophotometer absorbance at wavelength λ, l is the optical path length, and A(720nm) is the baseline correction. The spectral dependence of CDOM absorption is characterized by an exponential increase to shorter wavelengths with a maximum in the UV spectral range and can be described according to Jerlov (1976), and Kirk (1994) by the following

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equation:

$$ay(\lambda) = ay(\lambda_0)\exp(-s(\lambda - \lambda_0)),$$

where ay(λ) is the absorption coefficient at the wavelength λ, λ_0 is the reference wavelength and s the spectral slope for the exponential dependence. The absorption coefficient at 440nm is used for comparisons.

3 Results

3.1 Sea ice samples

Bulk salinity of the sea ice cores are summarized in Table 1. CTD and salinometer measurements of the melted ice core water are very close and, therefore, the CTD measurements appear to be reliable. The mean bulk salinity of the sea ice cores amount to about 0.6g kg^{-1} and the sea surface salinity at the ice core stations showed values between 2.95g kg^{-1} and 3.0g kg^{-1}.

The sampled brine volume at station 9 was too small for further analysis. Brine salinity for stations 8 and 10 is listed in Table 2. As for the ice core samples, salinity measurements by CTD and salinometer are very close to each other. The mean brine salinity is 14.7g kg^{-1}. Altogether, the sea ice measurements can be summarized as follows: The mean sea ice bulk salinity in the Bothnian Sea is about 0.6g kg^{-1}. Taking into account a sea surface salinity of 3.0g kg^{-1}, 2.4g salt are rejected from 1kg freezing sea water, while the rejected brine shows a salinity of 14.7g kg^{-1}.

The spectral absorption of CDOM was measured at samples from three ice stations (8, 9, 10, Fig. 3). Surface water samples from ice holes and CTD rosette were compared with brine and water from different melted ice layers — mainly top, middle and bottom layer. The absorption shows strong differences between ice samples, surface water, and brine. Highest values were measured in brine and lowest values in ice water while only little differences were found within the different groups. Absorption measurements of brine was possible only at station 10 due to low brine volumes sampled at stations 8 and 9. The measured spectra are shown in Fig. 4.

For the relation between CDOM absorption at 440nm and CDOM content estimated from Wetlabs CDOM fluorescence sensor (chap. 2.2), we derived a linear regression (Fig. 5). This regression can be used to calculate CDOM absorption from CDOM content and vice versa.

CDOM concentrations at station 10, estimated from the relation in Fig. 5, are listed in Table 3. Similar to salt, CDOM concentration increases in brine due to sea ice formation. However, the increase for salt (17.74g kg^{-1} : 2.95g kg^{-1}) is stronger than the increase for CDOM (103.99$\mathrm{mg\,m}^3$: 23.8$\mathrm{mg\,m}^3$). That is, relatively more CDOM remains in sea ice. Müller et al. (2011, 2013) show that CDOM in Baltic Sea ice is enriched compared to salt with an enrichment factor of up to 39%. Our estimates for station 10 show an enrichment of 50% to 70%.

3.2 Water column samples

Figure 6 shows temperature, salinity, oxygen, and CDOM profiles from stations 7, 9, 10, and 11 (see Fig. 3 for locations). In the Bothnian Bay, temperature near the surface is close to the freezing temperature. The upper 20m to 30m are well mixed

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Table 1. Ice core samples from stations 8, 9, and 10. Location shows which part of the core is used for analysis. Top, mid, and bot are the upper, middle and lower part of the ice core, respectively. Bulk is for the whole ice core. Sal.(C) and Sal.(S) are the absolute salinity measured with mini CTD and salinometer, respectively.

Stat. #	Core #	Location	Sal.(C) [g/kg]	Sal.(S) [g/kg]
8	1	top	0.81	0.86
8	1	bot	0.67	0.70
8	2	bulk	0.54	0.77
8	3	bulk	0.81	
8	4	top	0.93	0.80
8	4	mid	0.46	0.46
8	4	bot	0.73	0.78
9	2	mid	0.80	0.77
9	2	bot	0.48	0.48
9	3	top	1.38	
9	3	mid	0.60	
9	3	bot	0.38	
9	4	bulk	0.64	
10	1	top	0.82	
10	1	bot	0.58	
10	2	top	0.53	
10	2	bot	0.49	
10	3	top	0.73	0.71
10	3	bot	0.70	0.70

Table 2. Brine samples from stations 8 and 10. Sal.(C) and Sal.(S) are the absolute salinity measured with mini CTD and salinometer, respectively.

Stat. #	Sal.(C)	Sal.(S)
8	11.62	11.65
10	17.94	17.94

suggested by the density profiles. At the Northern Quark (station 11), stratification already starts below the surface, presumably due to out-flowing water which is continuously mixed with the underlying water from the Bothnian Sea. The weak stratification also existed below the sea ice measured with the hand-held mini-CTD through the bore holes (Fig. 7). Temperature stratification starts at a depth of about 25m. At station 9, a salinity stratification is already visible below 10m depth. The step like structure shows the resolution of the instrument due to digitizing.

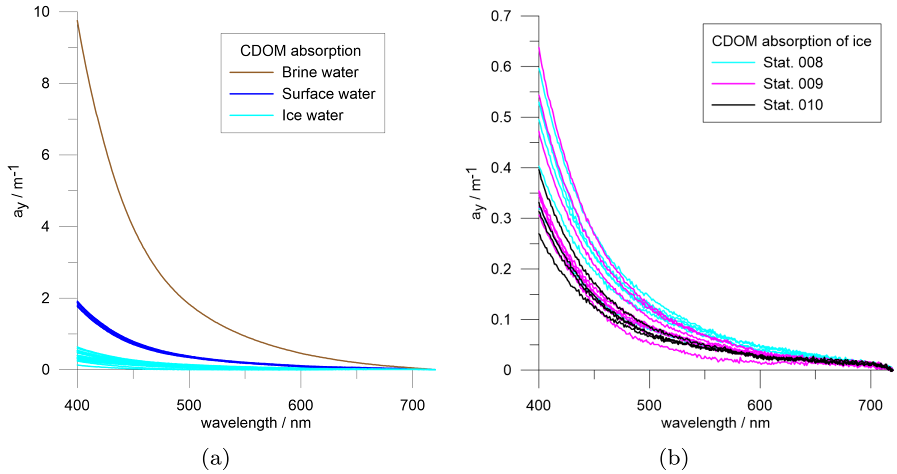

Figure 4. Spectral absorption at the sea ice stations including surface water from ice holes and CTD-rosette samples, brine, and water from different melted ice sheets at stations 8, 9, and 10 (Fig. 3). b) shows melted sea ice absorption separately.

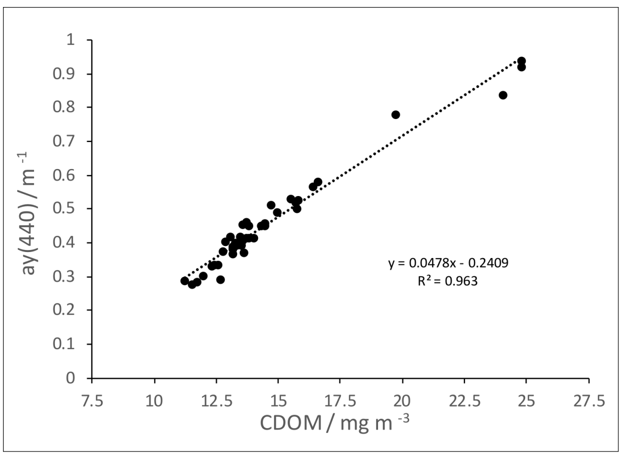

Figure 5. Linear regression between CDOM absorption at 440nm and CDOM content derived from Wetlabs CDOM fluorescence sensor.

Temperature and salinity increase at all Bothnian Bay stations with depth below the mixed layer while oxygen is decreasing, either due to salinity and temperature increase (still close to saturation concentration) or due to oxygen consumption. There is an exception at station 9, where a 20m thick layer above the ocean floor is well oxygenated, even slightly over-saturated, showing a very low temperature. We assume that this water mass was formed from water which recently was in contact with the sea surface and, therefore, indicate a ventilation event of the bottom water at station 9. To identify a possible genesis of this bottom water, we analyzed the temperature-salinity (TS) properties based on our CTD measurements.

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	a_y(440) m^{-1}	CDOM $mg\,m^{-3}$
Brine	4.73	103.99
Surface Water	0.898	23.8
Sea Ice (min)	0.14	7.97
Sea Ice (max)	0.175	8.7

Table 3. CDOM absorption and CDOM concentration in brine, water, and sea ice at station 10.

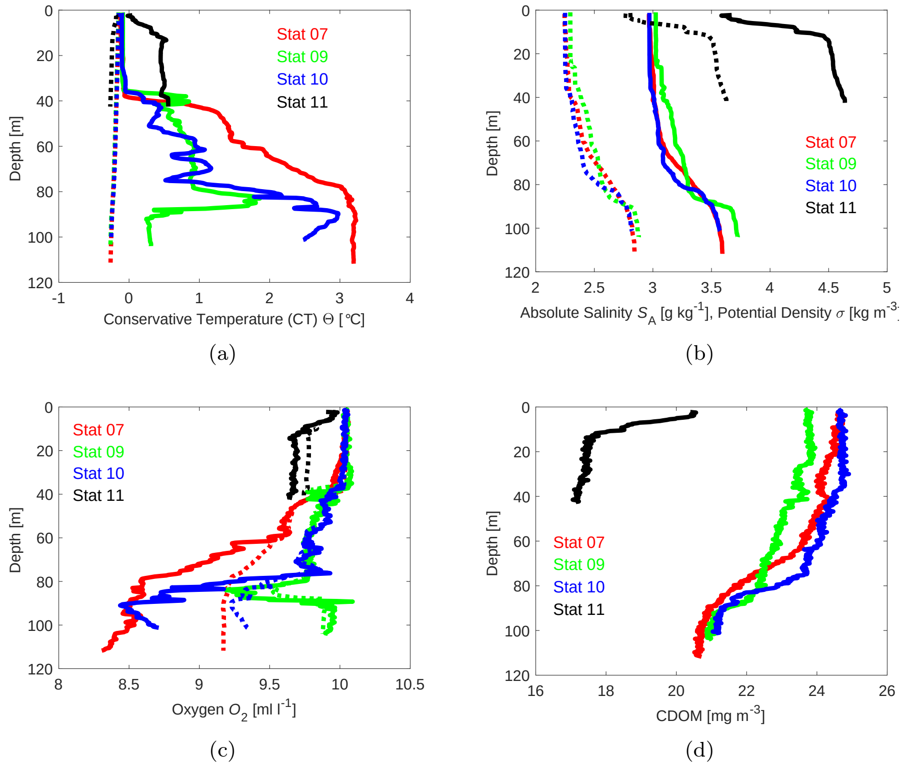

Figure 6. Shipborne CTD profiles at stations 7, 9, 10, and 11 (Fig.3) for conservative temperature (a), absolute salinity (b), oxygen (c), and CDOM (d). Dotted lines show the freezing temperature (a), the potential density (b), and the saturation oxygen concentration (c).

The TS characteristics are shown in Fig. 8. In addition to the Bothnian Bay stations, we included station 12 from the northern Bothnian Sea. Only data points with oxygen concentrations close to saturation and from station 12 only the upper 20m are included. This restriction is justified by the fact that the water mass of interest, the bottom water at station 9, is saturated with oxygen and the Northern Quark sill depth is shallower than 20m and constrains inflows from the Bothnian Sea.

The bottom water from station 9 (well oxygenated) is roughly in the middle of Fig. 8, where mixing lines are crossing. The light greenish, dashed lines are mixing lines showing water masses from the Bothnian Sea and Bothnian Bay which potentially

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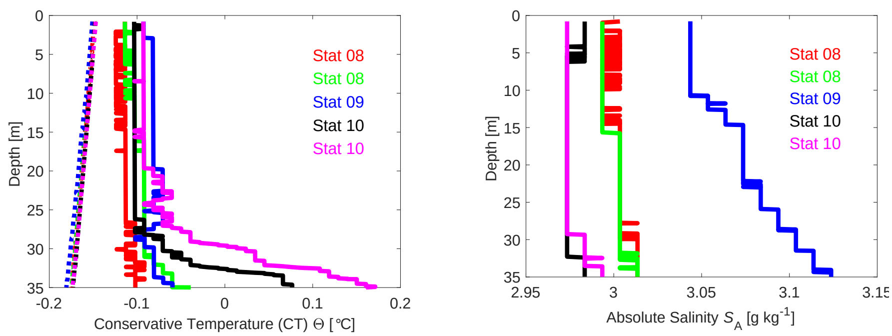

(a) (b)

Figure 7. Mini-CTD profiles at stations 8, 9, and 10 (Fig.3) below the sea ice for conservative temperature (a) and absolute salinity (b). Dotted lines are the freezing temperature (a). Two casts were performed at stations 8 and 10.

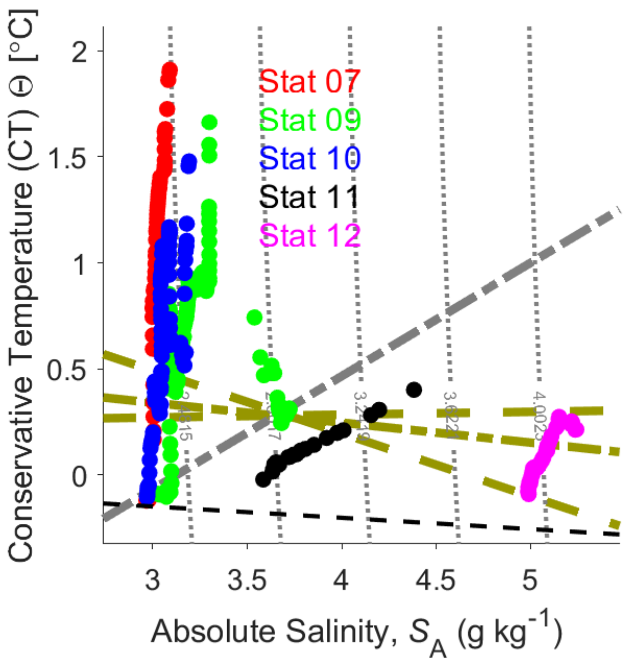

Figure 8. TS diagram for stations 7, 9, 10, 11, and 12 (Fig. 3). Gray dotted lines show the density. Greenish dashed and dash-dotted lines show mixing lines for station 9 bottom water from Bothnian Bay and Bothnian Sea surface water, and from Bothnian Bay water and brine, respectively. The gray dash-dotted line is for mixing of Bothnian Bay surface water and arbitrary, warmer Bothnian Sea water. Data points with oxygen concentration close to saturation are considered only. For station 12, data point are restricted to a depth shallower than 20m. The dashed black line is the freezing temperature.

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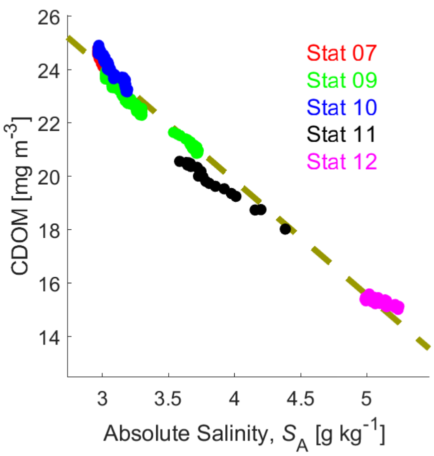

Figure 9. Salinity – CDOM diagram. The dashed line is the mixing line.

could have contributed to the bottom water at station 9. The surface water in the Bothnian Bay is close to freezing temperature down to 40m depth (Fig 6) and no candidate for forming the bottom water of station 9. The northern Bothnian Sea surface water is at the other end (right side) of the mixing lines. The greenish dash-dotted line in Fig. 8 is the mixing line, if brine and Bothnian Bay water would form station 9 bottom water. Based on the temperature constrains given by TS characteristics, we suggest that recent Bothnian Bay surface water was not contributing to station 9 bottom water. Another possibility is given by the gray dash-dotted mixing line in Fig. 8, assuming Bothnian Bay surface water was mixed with Bothnian Sea water. Apparently, much higher temperature (app. 1°C) in the Bothnian Sea would be necessary.

The salinity – CDOM relationship is shown in Fig. 9. The main source for CDOM in the northern Baltic Sea are yellow substances carried by rivers into the Baltic Sea. Yellow substances in the Baltic Sea are relatively refractory and, therefore, a linear CDOM salinity relation exists (e.g., Harvey et al., 2015).

4 Discussion

In March 2017, a well oxygenated and cold bottom water layer was observed at station 9 in the center of the Bothnian Bay (Fig. 6). The water column showed a pronounced density stratification mainly due to a halocline in about 80m depth with less oxygen than in the bottom water. Therefore, it is very likely that the oxygen rich water arrived at this position rather by lateral intrusion or inflow than by vertical mixing. In the sea ice covered Bothnian Bay, two mechanism potentially could have produced the observed water mass. (i) Bothnian Sea surface water crossed the Northern Quark, was mixed with Bothnian Bay surface water, descended to the bottom due to high density and followed the topography into the basin, or (ii) brine release from sea ice and ambient water formed a denser water mass, preferentially in shallower coastal areas, which then, as a gravity current, arrived at the deep basin.

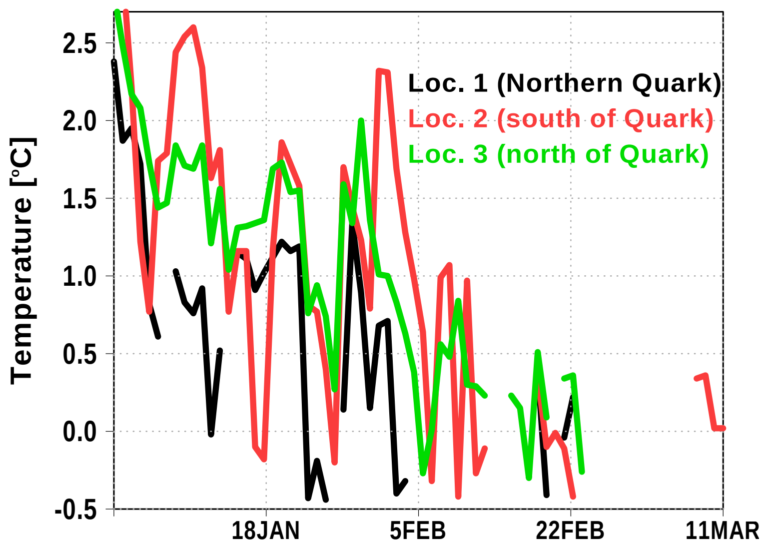

Figure 10. Satellite derived sea surface temperature at 3 locations in the Bothnian Sea/Bay in 2017. Location 1: 21.16E 63.75N, Location 2: 20.50E 63.15N, Location 3: 21.57E 63.91N. Data source: These data were provided by the Danish Meteorological Institute (DMI) and GHRSST via marine.copernicus.eu. Note: Data gaps are due to sea ice cover.

The low temperature and the very high oxygen concentration (Fig. 6) reveal that the contributing water masses were in contact with the surface recently. A TS analysis in Fig. 8 suggest that a mixing of the observed Bothnian Sea and Bothnian Bay water hardly can result in the observed oxygen rich, cold bottom water. Only a small portion of Bothnian Bay water in about 40m depth shows the appropriate TS properties. However, assuming temperatures in the Bothnian Sea would be higher, approximately about 1°C, surface water from the Bothnian Sea and from the Bothnian Bay can mix into the observed bottom water. Another possibility is that both water masses have a similar temperature of about 0.3°C.

We show in Fig. 10 the sea surface temperature (SST) development at three locations in the northern Baltic Sea. Location 1: directly at the Northern Quark, location 2: south of the Northern Quark, and location 3: north of the Northern Quark (Fig. 3 blue dots). These data are from a multi sensor satellite SST product. All SST data below -0.5°C have been masked out since it is well below the freezing temperature. We have to note that the SST data are potential temperature while our measured data are given as conservative temperature. However, differences between potential and conservative temperature in the given temperature and salinity range are very small (ICO et al., 2010).

There is hardly any situation where inflowing surface water from the Bothnian Sea shows a SST of about 1°C while at the same time in the Bothnian Bay the SST is close to the freezing temperature (-0.2°C). For the case that both mixing water masses are close to the temperature of the bottom water at station 9 (app. 0.3°C), a time window exists between February 18th and 22nd. However, we cannot say that during this time surface water from the Bothnian Sea flowed into the Bothnian

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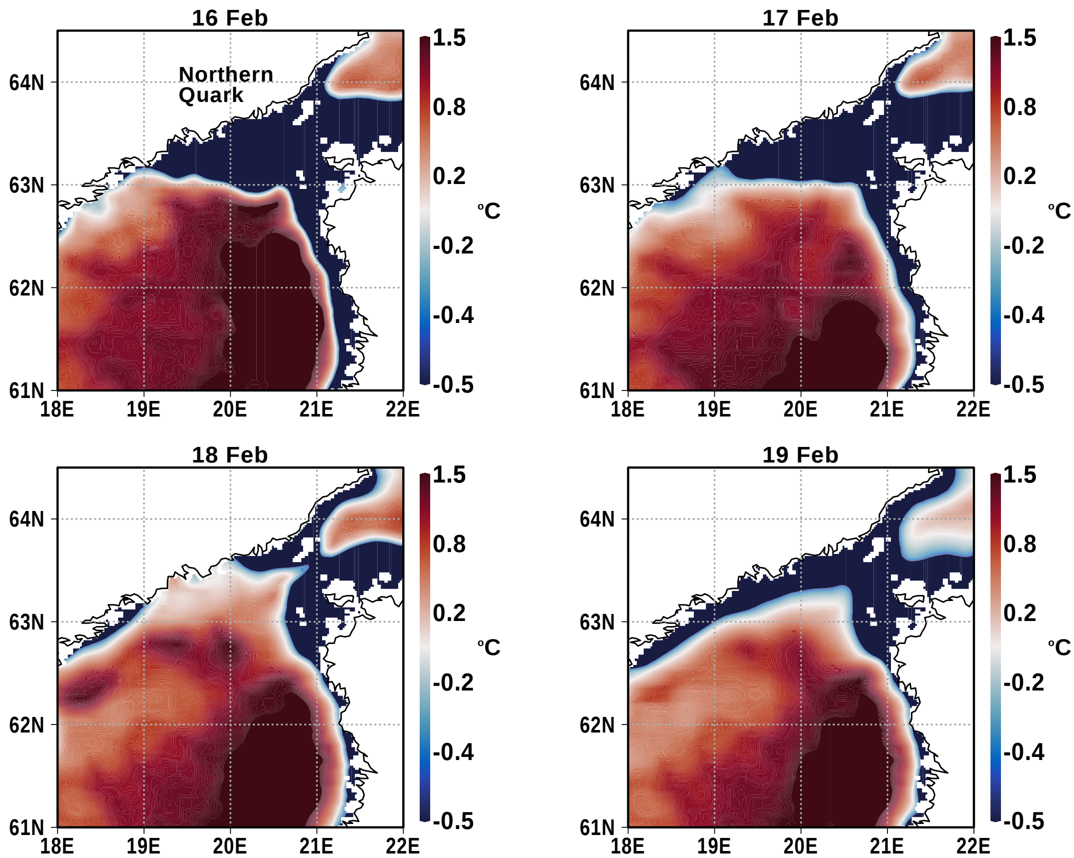

Figure 11. Satellite derived sea surface temperature for February 16th to 19th. Data source: These data were provided by the Danish Meteorological Institute (DMI) and GHRSST via marine.copernicus.eu. The maps were created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/).

Bay since we do not have information on surface salinity or currents. Consequently, there is a certain likelihood that an inflow between February 18th and 22nd has formed the observed bottom water at station 9.

At February 18th, warmer water is crossing the Northern Quark and some Bothnian Sea water plumes may have entered the Bothnian Bay, shown by satellite derived SST in Fig. 11. Strong westerly wind in the Bothnian Sea area (Fig. 12) has pushed water to the south at 17th February. Owing to a sudden weaken of the wind at 18th of February, water is flowing back to the north and some plumes may have crossed the Northern Quark (Fig.11). In summary, there are some indications that surface water from the Bothnian Sea have been mixed with Bothnian Bay water forming the observed bottom water at station 9 around 18th of February.

Harvey et al. (2015) show a linear relationship between CDOM fluorescence and CDOM absorption, and CDOM absorption and salinity (negative slope) in the Bothnian Sea, resulting in a linear relationship (negative slope) between CDOM fluorescence

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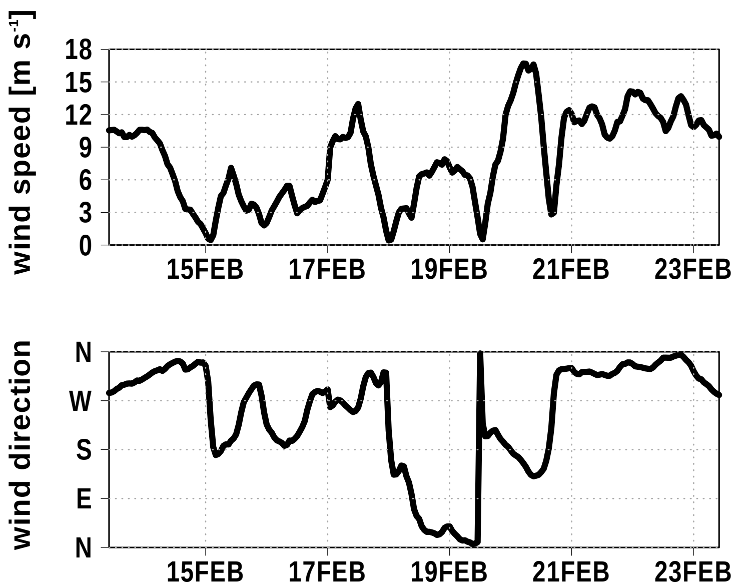

Figure 12. Average wind speed and direction over the Bothnian Sea. Data source: Deutscher Wetter Dienst (German Weather Service) (2019)

and salinity. Figure 9 clearly shows this relationship. Assuming that CDOM (yellow substances) are largely conservative, the bottom water at station 9 could be the result of mixing Bothnian Sea and Bothnian Bay water. For an analysis of water masses, we estimate the mixing ratio mx. mx is the volume ratio of Bothnian Bay surface water $\mathrm{S_{BS}}$ to Bothnian Sea surface water $\mathrm{S_Q}$ giving Bothnian Bay bottom water $\mathrm{S_{BB}}$ based on measured salinity.

$$mx = \frac{S_Q - S_{BB}}{S_{BB} - S_{BS}}$$

With the salinity of the surface water at station 12 $\mathrm{S_Q} = 4.9$, of Bothnian Bay surface water $\mathrm{S_{BS}} = 3.0$, and of Bothnian Bay bottom water at station 9 $\mathrm{S_{BB}} = 3.75$, mx gives 1.53. Using this mixing ratio, we can estimate the CDOM concentration in the Bothnian Bay bottom water: Given surface CDOM concentrations in the Bothnian Sea (15.4g $\mathrm{m^3}$) and Bothnian Bay (24g $\mathrm{m^3}$) result in a bottom water concentration in the Bothnian Bay of 20.6g $\mathrm{m^3}$. This value is close to the observed value of 21g $\mathrm{kg^{-1}}$ (Fig. 6).

Mixing of brine and Bothnian Bay surface water cannot decrease CDOM to the observed level. If CDOM behaves similar as salt during freezing, that is, concentration increases in brine, the mixed water would show an elevated CDOM concentration like salt. Müller et al. (2011) and Müller et al. (2013) show that CDOM is enriched in sea ice compared to salt. The enrichment factor of CDOM in sea ice relative to salt is in the order of 1.3. Therefore, the CDOM concentration in brine is less increased than salinity but still higher than in the surface water and a brine induced bottom water would have higher CDOM concentrations than the surface water.

Brine release, as a mechanism for deep water renewal, is observed especially in arctic fjords (e.g. Skogseth et al., 2008). Coastal polyniyas add salt to the water from sea ice production and density differences drive a downflow of the dense water to

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deeper basins. Brine plumes have been also observed below matured, fast sea ice if the sea ice temperature exceeds a critical temperature (Peterson, 2018). This could happen if sea ice is warmed either by air or from below by water. Owing to the warming, permeability increases and brine move through the ice being finally rejected (Golden et al., 1998). Rejected brine may not necessarily fully mix with the ambient water as assumed e.g. by Marmefelt and Omstedt (1993). Moreover, brine plumes may sink down to the sea floor or to a pronounced density stratification depending on the turbulent kinetic energy in the water (Smith and Morison, 1998; Morison and McPhee, 1998). Therefore, new and dense water masses can accumulate at the sea floor or at the pycnocline where as a result, the depth of the pycnocline decreases.

A simple budget calculation can provide a volume estimate for a bottom water mass produced by mixing of brine and ambient surface water. We use salt and volume conservation of the contributing water masses and derive a relation for observed quantities. We make the assumption that the surface salinity do not change between sea ice formation and later mixing with brine. With a sea ice density of $900\mathrm{kg\,m^{-3}}$, the sea ice thickness $\mathrm{H_I}$, and the Bothnian Bay area A, we can write:

$$V_{bot} = 0.9 \cdot A \cdot H_I \cdot \frac{S_w - S_i}{S_{bot} - S_w} \tag{1}$$

$\mathrm{V_{bot}}$ and $\mathrm{S_{bot}}$ are volume and salinity of the new bottom water, $\mathrm{S_w}$ is the surface water salinity, and $\mathrm{S_i}$ the bulk ice salinity. Using our observations $\mathrm{S_w}$=3.0$\mathrm{g\,kg^{-1}}$, $\mathrm{S_{bot}}$=3.72$\mathrm{g\,kg^{-1}}$, $\mathrm{S_i}$=0.6$\mathrm{g\,kg^{-1}}$ and assuming a basin wide ice thickness of 0.2m, the Bothnian Bay could be filled up to a depth of 93m with the newly generated bottom water. However, this is an upper estimate showing the amount of potentially produced bottom water. Not all of it will eventually arrive at the deeps of the basin and also our measurements show oxygenated water at station 9 only (Fig.6). Dividing the volumes in equation 1 by the area of the Bothnian Bay, one get an estimate of the thickness of the new water mass at the sea surface. Assuming again 0.2m sea ice thickness, the new bottom water would have a vertical extent of 0.6m. In areas shallower than the pycnocline, dense water can accumulate at the sea floor and form density driven plumes guided by topography.

In order to test this hypothesis, we analyzed data from the HELCOM monitoring program (www.helcom.fi) and provided by ICES. Station BO3 is close to our station 9 while station K is in the shallow coastal area (19m deep, Fig. 3). In Fig. 13, the bottom salinity for stations BO3 and K is shown. For station K, we separated the data into sea ice season (February, March, April, blue dots) and the rest of the year (red dots). For Station BO3, we show data from November and December just before the ice season usually starts (green dots). For the period 1985 until 2000, the bottom salinity in winter (blue in Fig. 13) is slightly higher compared to the summer values. One reason for the increased salinity in winter could be the formation of new water masses due to brine release. However, the bottom salinity in the coastal water (station K) do not exceed the bottom water salinity at station BO3 which is necessary to replace the old water by the new formed water. Consequently, we found no hint in the observations for coastal water masses which would be able to ventilate the deep basins. However, one have to be aware that the density plume formation is a short and rare event which may not be observed with standard monitoring strategies.

5 Conclusions and Summary

During a cruise in March 2017, we took sea ice samples in the northern Baltic Sea, the Bothnian Bay. The bulk ice salinity was about 0.6$\mathrm{g\,kg^{-1}}$. Brine samples showed a salinity of about 15$\mathrm{g\,kg^{-1}}$ and the surface water a salinity of about 3$\mathrm{g\,kg^{-1}}$. In

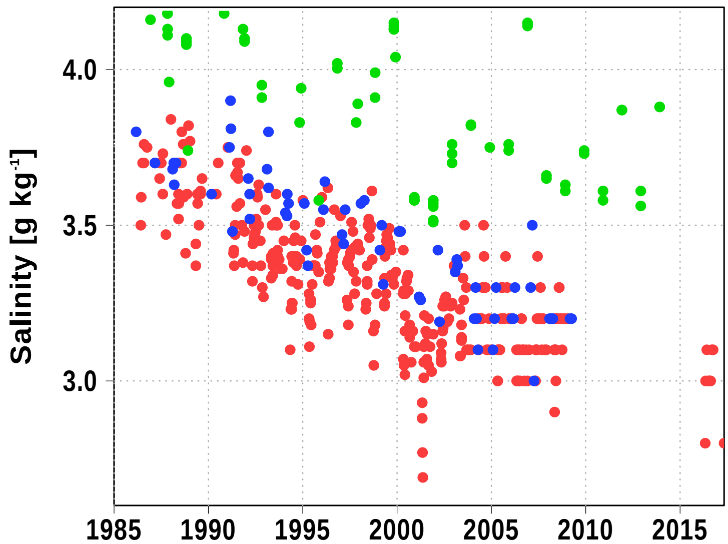

Figure 13. Bottom water salinity at stations B03 (green) and K (red, blue). Data are from Nov. and Dec (green), Feb., Mar., and Apr. (blue), and May to Jan. (red). For the location of stations see Fig. 3. Data source: ICES

addition, CTD casts were performed at 3 different locations. At one location, the bottom water was saturated with oxygen and the temperature was very low (0.25°C) compared to the other two stations. We assume that this bottom water was formed due to a recent intrusion of former surface water.

Owing to the bottom water mass properties, brine rejection could have formed the bottom water. Contrarily, CDOM measurements do not support this hypothesis. Also historical data do not show any hint that dense bottom water due to brine rejection is formed which is able to replace older water in the basin.

An alternative ventilation mechanism is the inflow of Bothnian Sea surface water into the Bothnian Bay. We found a possible time for such an inflow 3 weeks before our measurements and strong indications making it very likely that the observed ventilation is due to an inflow of surface water. This mechanism can only work if the sea surface salinity of the adjacent basin is considerably higher than the salinity of the bottom water. A prerequisite for this configuration is a shallow sill separating the basins. The depth have to be sufficient shallower than the halocline to prevent saline deep water inflows. These findings confirm Marmefelt and Omstedt (1993) who exclude haline convection for the Bothnian Sea based on budget estimates and considered this process as very unlikely for the Bothnian Bay.

The volume of the new oxygen rich bottom water appears very limited since we observed the high oxygen concentration only at one of three closely located stations. However, surface water inflows may happen more frequently than e.g. inflows of dense water into the central Baltic basins. The sea ice conditions during winter hamper continuous observations necessary to quantify the bottom water production in time and space. Consequently, there is still an urgent need for high quality observations in the northern Baltic Sea which will help to understand this ecosystem.

Data availability. All sea ice and brine data are available in this text. Data from the hand-held CTD and shipborne CTD data are available from http://doi.io-warnemuende.de/10.12754/data-2019-0002.

Author contributions. TN and MM designed the experiment, HS and MG performed optical measurements, MK and DN performed CTD and ice core measurements. All authors contributed to data analysis and writing the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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