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Revision os-2019-48

Dear John Huthnance (OS editor)

Hereby, I submit the revised version of the manuscript os-2019-48

Ventilation of the Northern Baltic Sea

by Thomas Neumann, Herbert Siegel, Matthias Moros, Monika Gerth, Madline Kniebusch, and Daniel Neumann.

First of all, we would like to thank the three anonymous referees and you for the careful consideration of the manuscript and many helpful comments. Following the referees' suggestions, we have extended the study with a numerical model experiment. We have taken into account every remark and worked through the whole text and think, the manuscript has much improved now.

An appendix with our detailed response to the reviewers' comments is attached at the end of the letter. Thank you for time and effort to consider the submitted manuscript.

With best regards,

Thomas Neumann

Appendix

Major changes of the revised manuscript:

The referees' main concern of the manuscript was the low number of observational data supporting our findings. For the revised version, we designed and performed numerical model simulations to increase the available data. The model simulation reproduces the campaign and in addition to temperature and salinity variables, a number of passive tracers, earmarking different water masses, were activated. Model results clearly support our hypothesis that dense bottom water is formed due to mixing of different surface water masses and that brine is not involved in this process. Since these results are well justified by the model simulation, we no longer consider satellite data and *in situ* monitoring data.

We included an assessment for model performance in the northern Baltic Sea as an appendix.

Detailed response (in blue color) to the comments of the referees

Referee #1:

Abstract. The abstract is not sufficiently informative. Basically, there is just one sentence, which describes, what this paper is about. I would suggest to exclude all general wording about the Baltic Sea, but to add more about the essence of this paper.

We revised the abstract and more information, especially about the model simulation, is given. General information about the Baltic are reduced.

Page 2, lines 2-3: I would suggest to add more detailed explanation (not just reference on Peterson, 2018), how melting sea ice can produce considerable salt fluxes into the ocean? This is quite a new knowledge, and it is important to explain it in more details.

We added ideas of Peterson (2018) on brine release during melting. Basically, increasing permeability enhances gravity forced drainage.

Page 2, lines 3-4: The references to Aagaard,et al., (1981) and Skogseth et al. (2008) are not relevant in this context. These papers describe specific events of dense water formation and do not consider general theory of this event at all. Taking into account that the authors are considering horizontal advection, as the most probable mechanism of the surface water densification in the Bothnian Bay, I would suggest them to read papers by Shapiro et al (2003) and Ivanov et al. (2004), which summarized all known mechanisms of dense water formation and cascading (not only in the Arctic, but worldwide).

We would like to thank the referee for additional literature recommendations. Now, the introduction starts with the general consideration of deep water ventilation. However, we think that examples of case studies from sea ice regions are useful for our study.

Page 15, lines 19-20: "In areas shallower than the pycnocline, dense water can accumulate at the sea floor and form density driven plumes guided by topography" This is very speculative statement, which is not confirmed by the provided measurements, but only by the references to the older studies, where this idea was also rather claimed, but not strongly supported.

The referee is right. We skipped this statement, since the model simulation clearly excludes such mechanism for ventilation.

<u>Referee #2:</u>

General comments:

- The layer close to bottom at one station (station 9) is marginally interesting. Clearly one would have wanted more than one station to show the persistence of any suggested process.

This argument is certainly true but there are not so many observations. The model simulation, now available, gives more confidence in the findings and show that oxygenated bottom water layer at one station was just the beginning of the winterly ventilation process.

This water is high in oxygen, but also 0.5 deg C above freezing. This indicates that it is not related to sea ice formation, or brine driven convection.

Here we disagree with the referee. When brine mixes with surface water and vertically subsides, it preserves most probably the surface temperature. If the new water mass then horizontally spreads or moves downslope, entrainment of warmer deep water changes the temperature. However, we do not discuss this process anymore since it was rejected by the model simulation.

So why is all the sea ice observations included? Really – it has no use as the paper is written at the moment. Obviously the authors would have liked to find evidence for the "brine hypothesis" – but they have not.

Yes, this was one of the motivations for the sea ice observations. We wanted to test the hypothesis whether brine contributes to deep water formation in the northern Baltic. We have formulated the hypotheses more pronounced in the revised manuscript.

Additionally, only little data are available for this region from wintertime. Thus, our intention was also to make this observations public available.

- There is generally a small number of citations given. While it is good practice not to overflow with too many, here it is on the sparse side. And one suspects that the authors have spent a limited effort on finding relevant studies. A good example is for the experimental studies in polynyas (Page 2, line 5). Clearly there are many more observations available from polynyas, both in the Arctic and Antarctica. As noted by the other reviewer are also some literature on the down-flow required. Examples on earlier polynya studies are given at the end. In general is there also much more available studies of Baltic sea ice available, where the few seas ice samples could be compared to.

We thank the referee for this recommendation. More general literature on down-flow processes and Baltic specific literature are included in the introduction.

Specific Comments:

Page 2, line 7. The Arcic is a name, should always be spelled with capital A. Correct throughout.

Changed accordingly.

Page 3, line 6: Use of "Fast ice" is wrong. Fast ice means sea ice frozen onto the shore. Here I think you mean pack ice? https://www.jcomm.info/index.php?option=com_oe&task=viewDocumentRecord&docID=14598

We agree, "pack ice" is right. Changed accordingly.

Page 3, line 11 It is not clear how you sample the brine. You state that:" holes approximately half the depth of the ice thickness were drilled to collect brine". Do you mean that you take out the core, and wait for water to drain back into the whole? How do you know this is the brine? The brine salinity is very tricky to sample, and conditions here are very special with the super low surface salinities.

The brine sampling was like the referee assume. We have described the sampling procedure more explicitly. We are quite sure that we sampled brine. What else could have caused the high, measured salinity? Of course, the sample could be polluted by snow. However, we took care and remove snow from the vicinity of the sampling station.

Page 4 – lower 4 lines. You simply state you used the (standard) Guildline's Autosal 8400B and the accuracy. It is a standard procedure in the field.

Changed accordingly.

Page 4 –line 8: Are you sure you closed the bottles on the way down? With higher pressures this would lead to the bottles imploding, so the standard is to do this on the way up.

Yes, we are sure; exception is the surface bottle because of possible air bubbles included. Doing so, we prevent samples from the wake of the down cast. Pressure differences are not so large in the shallow Baltic Sea.

Page 6 –line 7: What do you mean by; "CTD and salinometer measurements of the melted ice core water are very close and, therefore, the CTD measurements appear to be reliable"? How can you take a CTD measurement of the melted ice core? A CTD needs to be fully submerged in ocean water to work, and measures the conductivity over a much larger volume of water that is inside the conductivity cell. . .

We used the handheld (mini) CTD for these measurements. The conductivity cell is very small compared to the sample water volume. We described the procedure more explicitly in the "methods" section.

Page 6 – line 12; "The mean sea ice bulk salinity in the Bothnian Sea is about 0.6g kg-1". This is a very strong claim when you have ice cores from 3 locations. . ...

We reformulated this statement: - mean sea ice bulk salinity of the sampled cores -

Page 8, Figure 4 caption: ice sheets – this means the large piece of ice on Greenland and Antarctica. You may mean "ice core"?

We call it "ice core slices" now to prevent misunderstanding.

Page 10. Figure 7. The mini CTD observations appear close to the ship-born CTD. If they are plotted in the same figure – then one could see if there are any differences – but this appears not to be the case. This figure is not valuable – unless there are some significant differences – and then these should be shown in Figure 6.

We thank the referee for this recommendation. Indeed, differences are not visible in a figure. Therefore, we skipped a figure with data from the mini CTD and mentioned that the results are very close instead.

Figure 8: Is this the ship CTD data? Why then is not the warmest water on Station 10 and 12 about +3 deg C visible? And

Since we are interested in the water body with oxygen concentration close to saturation, we excluded all TS data points with oxygen well below saturation. Therefore, these data are not shown in Fig. 8. It is explained in the text.

Page 12 – line 10. Please use one temperature throughout a paper. It is fine to use the new conservative temperature, but then you should use it throughout.

Changed accordingly.

Page 13 – line 1: "we do not have information on surface salinity or currents." This is exactly the main problem. Very little data is available, and then one cannot really conclude on the suggested processes either. A numerical model could have amended this in a nice way.

We are very grateful for suggesting a complementary model study. Model results make the study much more concise now.

Page 13 – line 6: Also here; "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". Some anecdotal indications are not really enough to claim that one has new findings worth publishing in an international journal.

We think, with the help of numerical simulations, the status of "anecdotal indications" has been left.

Page 14, line 11-16: While I am no expert in biological processes it is clearly possible that there is growth of organic mater in sea ice, and this should be discussed. A fairly new paper (Assmy et al 2017) also finds that phytoplankton can also grow below a snow cover.

The referee is right; phytoplankton can grow within and below sea ice. However, the vast majority of CDOM in the northern Baltic Sea constitutes of refractory, terrestrially gelbstoff in high concentrations. Autochthonous CDOM plays a minor role only. Therefore, CDOM can be used as a conservative tracer in the northern Baltic Sea (e.g., Harvey, 2015).

Page 14, line 18: polyniyas is spelled wrongly.

Changed accordingly.

Page 14, line 17 – Page 15, line 7. While this is possible in the Bothnian Bay – you do not have any observations that indicate that this is going on. IF you added some simulations that this is likely, then this text could remain – otherwise it should be deleted.

The model simulation show that brine is not contributing to deep water ventilation. We deleted this text.

Page 15, line 8 – 20. This section finally contains some calculations about the brine water "hypothesis". The calculations appear OK - but does not use a proper range in forcing and boundary conditions. How representative is the 0.2 m of ice thickness? Is there any freshwater discharge during winter?

Since the brine hypothesis has been rejected, we deleted these calculations.

Suggested citations – there are many more:

We are very grateful for the comprehensive list of recommended studies which we have considered carefully.

Referee #3

This paper tries to justify that oxygen rich bottom water found in one profile collected in the Bothnian Bay, may have been formed by inflowing water from the Bothnian Sea mixed with surface water in the Northern Quark, and not by salt release from sea ice. The data set is very small, and the processing done poorly explained. It is also hard from the discussion to grasp that the above explanation is what the authors want to say. To make this manuscript more readable they should state more clearly in the discussion whether each explanation they try own ends up with a plausible explanation. I do not suggest any places where to do this in particular, but both the abstract and discussion and conclusions should become clearer. Perhaps add your hypotheses at the end of your introduction. Than it would be easier to state of your data support or do not support each of the hypotheses.

We thank the referee for the careful consideration of our manuscript and the useful suggestions. In the revised manuscript, we included model simulations and formulate hypotheses and there acceptation/rejection more clearly.

Page 3, line 12: Explain how you collected the brine.

Changed accordingly.

Page 4, Figure 3 caption: at (red crosses) to stations 7-10.

Changed accordingly.

Page 4, lines 1-2: Explain more elaborate how you measured salinity in both ice core samples (Table 1) and brine samples (Table 2). For instance how big did the samples have to be to measure salinity with the CTD. Also, with the low number of samples you collected, why not measure all with the Guildline?

We explained the salinity measurements more detailed. E.g., 100ml samples were sufficient for salinity measurements with the mini CTD. First, we did test measurements with both Autosal and mini CTD. Since both methods delivered the same data, we decided not to measure all samples with the Autosal.

Page 4, lines 2-7: The Guildline Autosal is a standard instrument used with a standard procedure, so this procedure does not need elaborate description. How you collected ice samples and brine and measured their salinity is on the other hand not standard procedure and needs better description.

Changed accordingly.

Page 5, line 10: Justify how you can assume that ‘upper 5m are well mixed and saturated with oxygen’. This might be ok for late winter, although I do not have any reference to recommend.

The only justification is that density and oxygen profiles are homogeneous in the 5m surface layer and do not show any stratification. The assumption is that in winter oxygen production/consumption is negligible compared to surface flux. We explicitly mention the “no stratification” criterion in the text.

Page 6, lines 13-14: Can you justify the assumption that all the rejected salt is trapped in brine pockets inside the ice? Some of it can be released into the water column.

Most of salt is released into water already. (2.4g of 3.0g salt in 1kg frozen sea water is released to the water column) We made this assumption more clearly in the revised text.

Page 6, line 14: You can hardly regard an average of two brine samples an average (14.7g/kg). At least, remove the decimal.

We agree. It is the mean of **our** samples and we removed the decimal.

Page 7, line 2: from where and to where is the water ‘out-flowing’. I would find the term ‘in-flowing’ more appropriate if it flows from the Bothnian Sea into the Bothnian Bay.

Here we mean low saline water from the Bothnian Bay layers above Bothnian Sea water. We improved the wording.

Page 7, line 2, last words: Change to ‘A weak stratification’

Changed accordingly.

Page 9 and 10, Figures 6 and 7: Try to use colors that are more easy to separate from each other. Especially Stations 9 and 10 with purple colors.

We use now green for station 9 und blue for station 10.

Page 9, line 6: Mixing lines do not ‘show’ water masses. They indicate along which line a mix between two source water types can be placed.

We thank the referee for this hint and improved our sloppy formulation.

Page 10, Figure 8: It is confusing when the end points of the mixing lines go beyond the source water masses. It is clear where the end water mass is, but not the source water masses. You should also indicate better which ‘greenish dashed and dash-dotted’ lines you are referring to in each case. Where is the brine in this figure, having which temperature? Etc.

We revised the figure. Brine is outside the figure. The used TS properties of brine are given in the figure caption and text.

Page 11, Figure 9: in this figure, the colors of stations 10 and 12 are difficult to distinguish.

The referee probably means stations 7 and 10. We note in the figure caption that station 7 data are mostly covered by station 9 and 10 data. Station 10 is in blue color and station 12 in violet color.

Page 11, line 3: The brine must be way beyond the axis in Figure 8. Again, which TS characteristics do you assume in the brine?

The assumed TS characteristics are now given in the text and figure caption.

Page 11, line 15: ‘mechanisms’

Changed accordingly.

Page 13, line 5: ‘weakening’

Changed accordingly.

Page 14, line 18: ‘polynyas’

Changed accordingly.

Page 15: make it clearer which formation process you trust and which you do not trust.

Changed accordingly.

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 CTD profiles and bottle samples, ice core samples, ~~brine, and CTD profiles. The bulk sea ice salinity was on average 0.6and in brinesamples, a salinity of 11.5~~and ~~17.8~~brine. In addition to hydrographic standard parameters, light absorption 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~~ in all samples. A complementary, numerical model simulation provides quantitative estimates of the spread of newly formed bottom water. The model uses passive and age tracers to identify and trace different water masses. Both observations and model simulation show that the Bothnian Bay is ventilated by dense water formed 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~~ initializing lateral inflows. These events occur during winter time when the water temperature is low. Brine is virtually not contributing to 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), and as a result, the surface salinity ranges from 14$\mathrm{g\,kg^{-1}}$ (south) to 2.5$\mathrm{g\,kg^{-1}}$ (north). 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).

The common prerequisite for deep water renewal due to inflows (cascading) is a sufficient lateral density gradient and slope of the ocean floor. A comprehensive summary of possible mechanisms producing density gradients and theoretical aspects for the initiation of cascades is given in Shapiro et al. (2003). In case of the northern Baltic Sea, salinity difference is the main driver for lateral density gradients. Small temperature differences close to the temperature of maximum density during winter do not have a remarkable effect on density compared to the effect of observed salinity gradients.

The bathymetric structure of the Baltic Sea is characterized by connected basins separated by shallow sills (Fig. 1). Cascades of descending water may be initiated if the density of water over the sills exceeds the density of the adjacent basin sufficiently. The depth of final interleaving depends on the lateral density difference and the entrainment on the way of the dense water plume. Stigebrandt (1987) estimates the entrainment into dense bottom currents of the Baltic Sea as a function of the slope (eq. 3.12 in (Stigebrandt, 1987)). For the central Baltic Sea, Major Baltic Inflows (e.g., Mohrholz, 2018) are the dominating process for bottom water ventilation. The origin of the new water mass is the North Sea; it leaves the surface in the western Baltic Sea and spreads northwards as a dense bottom plume.

Marmefelt and Omstedt (1993) investigate processes for deep water renewal in the northern Baltic Sea and ~~concluded~~ conclude that inflows of dense water are the main process rather than vertical convection. In contrast to ~~major Baltic inflows for~~ Major Baltic Inflows in 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~~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.

~~Haline convection is initiated by brine rejection during the sea ice season~~Geological studies from the Baltic Sea (Moros et al., 2020) indicate that deep water formation cause widespread re-suspention and transport of sediment during colder climatic periods. Sediment contourite drifts are prominent in depths greater than 200m in the Gulf of Bothnia and the northern Baltic Proper and therefore, cold conditions appear to favor dens water production. In fact, one cannot compare today's climate with conditions during the Little Ice Age (e.g., Kabel et al., 2012) when widespread sea ice dominated the Baltic Sea in winter. Today, the Baltic Sea shows conditions where sea ice appears regularly and surface water is cooled down to freezing temperature in the Bothnian Bay only. However, a mechanistic description of the detected sediment redistribution is still lacking.

In addition to dense water formation due to saline water from adjacent seas as described by Marmefelt and Omstedt (1993), dense water also can be formed due to brine from sea ice formation. It is an usual phenomenon in ~~arctic and subarctic~~ 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,~~ . Peterson (2018) observed a substantial salt loss in Arctic sea ice due to warming. The explanation is an increased permeability which allow for a gravity drainage. The general idea of new water mass formation due to brine 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)~~(Aagaard et al., 1981; Ivanov et al., 2004;
. However, owing to the rough weather conditions, experimental studies are sparse.

~~Owing to the low salinity, sea~~ Sea ice in the northern Baltic Sea shows a considerably lower bulk salinity compared to sea ice in the ~~arctic ocean~~ Arctic ocean due to the low sea water salinity. Usually, values less than $1\,\mathrm{g\,kg^{-1}}$ have been observed (e.g., Meiners et al., 2002; Granskog et al., 2005). ~~Therefore,~~ In addition, Baltic Sea ice can consists of up to 35% metamorphic

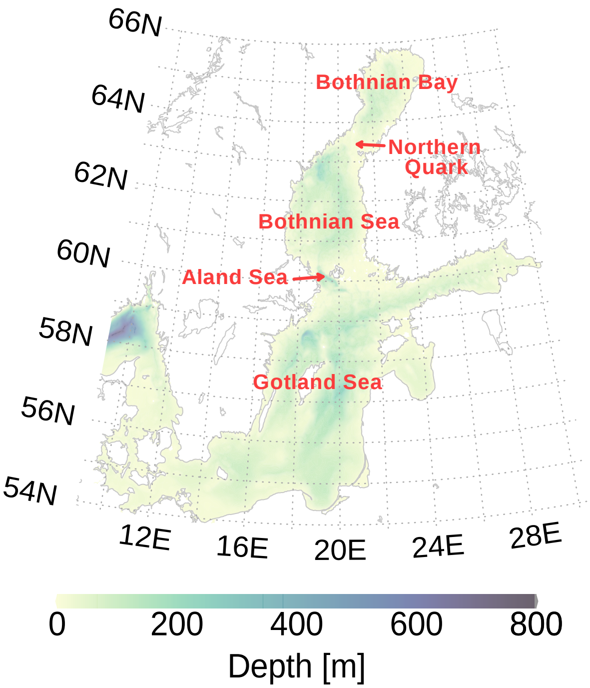


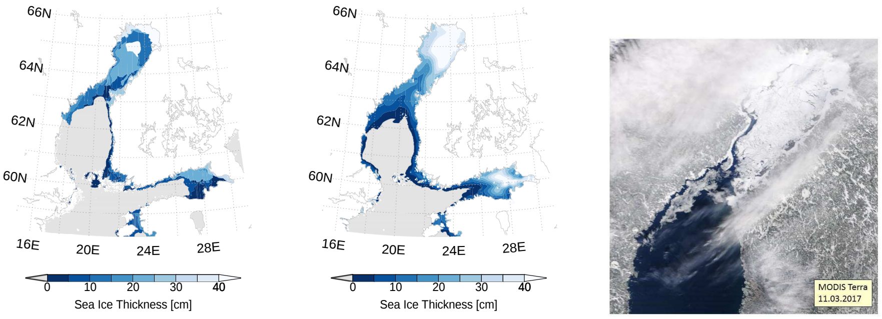
Figure 1. Bathymetry of the Baltic Sea showing names of different geographic regions we will use in the text. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).

snow (Granskog et al., 2006) and therefore, the brine volume in Baltic Sea ice is smaller than in ~~arctic sea ice, however,~~ 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 and bottle samples have been taken and analyzed. Furthermore, we performed numerical model studies to reproduce the campaign and to provide additional data for analysis. The aim of this study is to identify relevant processes ventilating the deep water of the Bothnian Bay and to quantify the importance of brine for dense water formation.

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



(a) (b) (c)

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). (b) is the same as (a) but from our model simulation. Sea ice coverage (~~b~~c), quasi true color image derived from MODIS at March 11th 2017. The map in (a and b) was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/)

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~~ pack 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~~performed. 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 .~~; the ice core was removed and brine drained from the ice collecting in the hole. After about 30 minutes, we took the brine sample from the borehole with a pipette. 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 was filtered and samples were prepared for analysis of yellow substances. Salinity of the ice cores and brine was measured with a hand-held CTD (see section 2.2). Owing to the size of the sensor pack, a small sample volume of about 100ml was sufficient. In addition, selected salinity samples (Tab. 1) 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~~

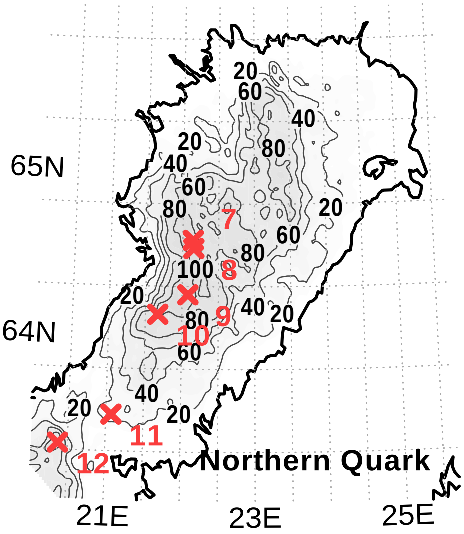


Figure 3. Locations of stations (red crosses) in the Bothnian Bay (stations 7 to 10), the Northern Quark (station 11), and the Bothnian Sea (station 12). Stations 7, 11, and 12 were CTD only stations. At stations 8, 9, and 10 sea ice and brine samples were taken. Nearby stations 9 and 10 also a CTD cast 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).

~~temperature during analysis, avoiding the need for temperature compensation. The accuracy is~~ The accuracy of the Autosal is better than 0.002 Equivalent Practical Salinity Units (PSU) ~~.~~

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 $370/460\,\mathrm{nm}$ 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~~ pumping system and water samplers. 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 5m are well mixed and saturated with oxygen~~. That is,~~ , i.e. a small offset has been applied to all oxygen profiles. This assumption was made on the basis of temperature and salinity profiles (Fig. 7) which are homogeneous in the upper layer.

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~~ kg and the small housing diameter of ~~48mm~~48mm, the probe is well suited for ~~a deployment~~ deployments 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°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 10cm cuvette using a dual-beam Perkin Elmer Lambda 2 instrument in the wavelength range between 300 and 750nm with increments of 1nm. Milli-Q water was the reference. Comparisons between Whatman GF/F and membrane filters with a pore size of 0.2µm 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 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.

2.4 Model simulations

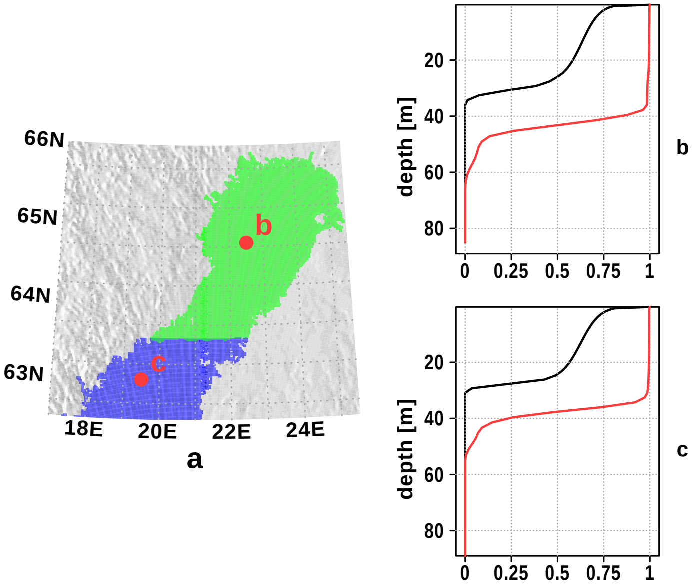


Figure 4. Initializing of the surface tracer in the northern Baltic Sea: Horizontal extent a) of Bothnian Sea surface tracer (blue) and Bothnian Bay surface tracer (green), and vertical extent at b) and c). Shown is the vertical profile after 1 day (black) and after 10 days (red).

For the analysis of different water masses, we use a 3-dimensional, numerical model of the Baltic Sea. The model code is MOM5.1 (Griffies, 2004) adapted for the Baltic Sea. The horizontal resolution is one nautical mile. Vertically, the model is resolved into 152 layers with a layer thickness of 0.5m at the surface and gradually increasing with depth up to 2m.

The circulation model MOM5.1 is coupled with a sea ice model (Winton, 2000) which accounts for ice formation and drift. Brine rejection is simulated by a sea surface salt flux. With a prescribed bulk ice salinity, the surplus salt is rejected immediately during freezing. Owing to the numerics of ocean models (grid spacing in the order of kilometers and the hydro-static approximation), the models cannot resolve microscopic processes like brine release. Therefore, we implemented a parametrization for the subgrid-scale convection of brine proposed by Nguyen et al. (2009). The parametrization distributes rejected brine within the mixed layer vertically simulating convective salt plumes. We used the calibration of Nguyen et al. (2009) for this study.

For earmarking water masses, we used the capability of the MOM5.1 model to define passive tracers which are set to unity at the surface at each model time step. Two passive tracers, each for the Bothnian Bay and the Bothnian Sea, are set up. Figure 4 shows the horizontal and vertical extent of the passive tracers. Owing to vertical mixing, the passive tracer is evenly distributed over the mixed layer after a few days of simulation. In addition, we have defined an age tracer for each passive tracer. The age of the corresponding tracer is set to zero at the surface at each model time step and otherwise increases with each time step. Furthermore, we defined two brine tracer for the passive tracer regions. The brine tracer represent the salinity rejected from sea ice during freezing. That is, the brine tracer is the salinity share due to brine.

The model has been forced by meteorological data from the coastDat-2 data set (Geyer and Rockel, 2013). We run the model from 1940–2018 and the passive tracer have been activated in January 2017. In many studies, the model have been successfully applied (e.g., Neumann, 2010; Neumann et al., 2015). An assessment for the model performance in the northern Baltic Sea is given in appendix A.

3 Results

3.1 Sea ice samples

Bulk salinity of the sea ice cores are summarized in Table 1. ~~CTD and salinometer measurements~~ Salinity measurements with the salinometer and the mini CTD of the melted ice core water are very close and ~~,~~ therefore, the mini CTD measurements appear to be reliable. The mean bulk salinity of ~~the sea ice cores~~ our sea ice samples amount to about 0.6 g kg^{-1} and the sea surface salinity at the ice core stations showed values between 2.95 g kg^{-1} and 3.0 g 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~~ with mini CTD and salinometer are very close to each other. The mean brine salinity is ~~14.7~~about 15 g kg^{-1}. Altogether, the sea ice measurements can be summarized as follows: The mean sea ice bulk salinity ~~in the Bothnian Sea~~ of our samples is about 0.6 g kg^{-1}. Taking into account a sea surface salinity of 3.0 g kg^{-1}, 2.4 g salt are rejected from 1 kg ~~freezing sea water~~ frozen sea water into the water column, while the rejected brine shows a salinity of ~~14.7~~15 g 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. 5.

For the relation between CDOM absorption at 440 nm and CDOM content estimated from Wetlabs CDOM fluorescence sensor (chap. 2.2), we derived a linear regression (Fig. 6). 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. 6, are listed in Table 3. Similar to salt, CDOM concentration increases in brine due to sea ice formation. However, the increase for salt (~~17.74~~17.94 g kg^{-1} : 2.95 g kg^{-1}) is stronger than the increase for CDOM (103.99 mg m^3 : 23.8 mg m^3). That ~~is~~means, 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%.

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.

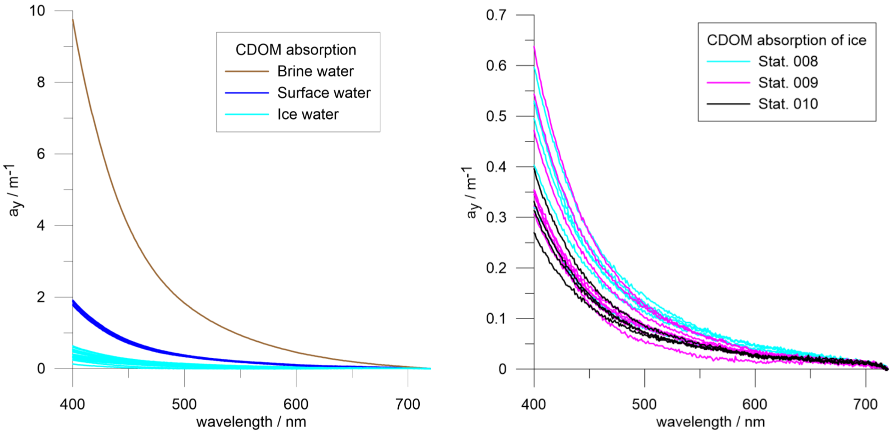
Stat. #	Core #	Location	Sal.(C) [g/kg]	Sal.(S) [g/kg]
8	1	top	0.81	0.86
8	1	bot	0.67	0.70
8	2	bulk	0.54	0.77
8	3	bulk	0.81	
8	4	top	0.93	0.80
8	4	mid	0.46	0.46
8	4	bot	0.73	0.78
9	2	mid	0.80	0.77
9	2	bot	0.48	0.48
9	3	top	1.38	
9	3	mid	0.60	
9	3	bot	0.38	
9	4	bulk	0.64	
10	1	top	0.82	
10	1	bot	0.58	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

3.2 Water column samples

Figure 7 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 suggested by the density profiles. At the Northern Quark (station 11), stratification already starts below the surface, presumably due to ~~out-flowing water~~ water from the Bothnian Bay which is continuously mixed with the underlying water



(a) (b)

Figure 5. 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~~ core sections at stations 8, 9, and 10 (Fig. 3). b) shows melted sea ice absorption separately.

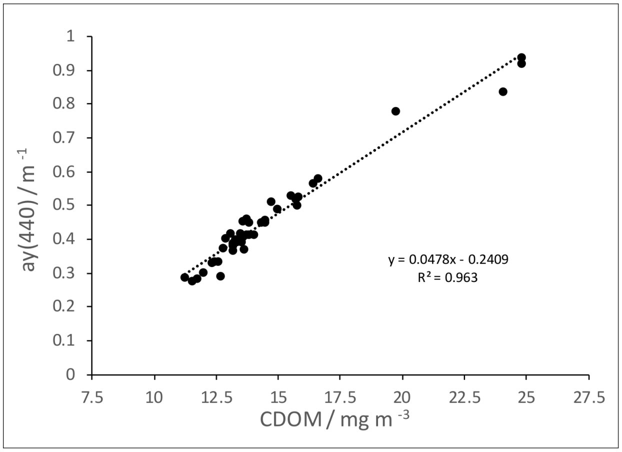


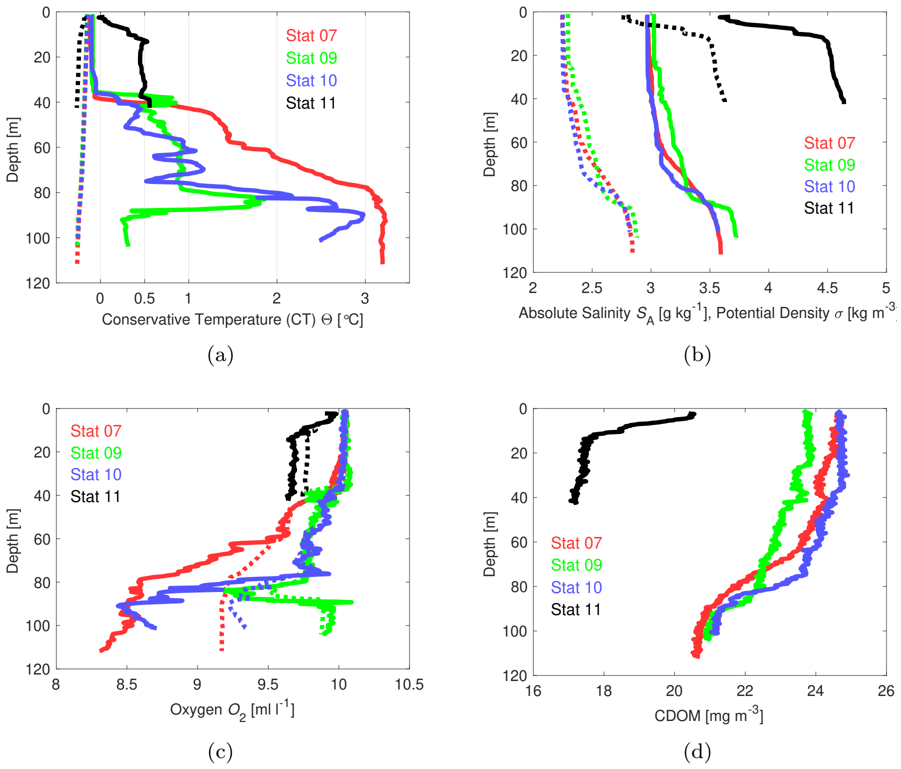
Figure 6. Linear regression between CDOM absorption at 440nm and CDOM content derived from Wetlabs CDOM fluorescence sensor.

from the Bothnian Sea. ~~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. The~~ A weak stratification also existed below the sea ice measured with the hand-held mini-CTD through the bore holes~~(Fig. ??).~~. 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~~We do not show the data since they are very similar to the data measured with the shipborne CTD.

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

	$a_y(440)\ \mathrm{m}^{-1}$	CDOM $\mathrm{mg\,m}^{-3}$
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

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



(a) (b)

(c) (d)

Figure 7. 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).

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.

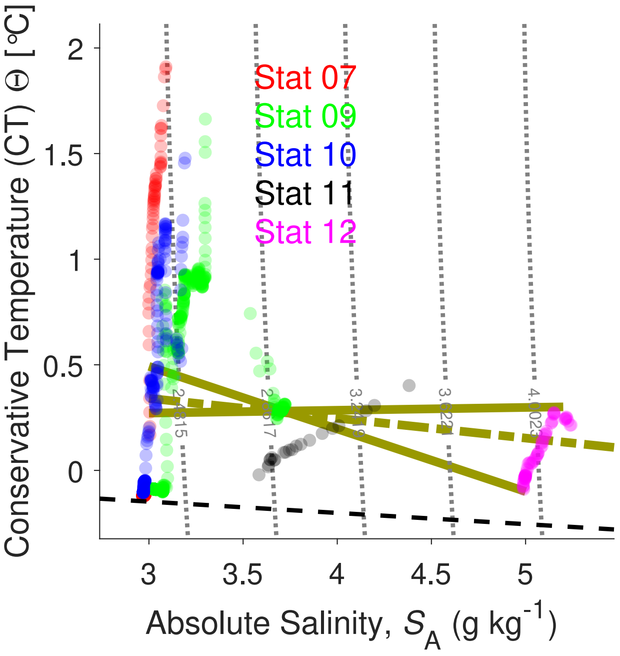


Figure 8. TS diagram for stations 7, 9, 10, 11, and 12 (Fig. 3). Gray dotted lines show the density. Greenish ~~dashed~~ solid and dash-dotted lines show mixing lines for station 9 bottom water from Bothnian Bay and Bothnian Sea surface water, and from Bothnian Bay water and brine, respectively. ~~The gray dash-dotted line~~ Brine is ~~for mixing of Bothnian Bay surface water~~ outside the figure with SA=15g kg^{-1} and ~~arbitrary, warmer Bothnian Sea water~~ CT=-0.79°C. Data points with oxygen concentration close to saturation are considered only. For station 12, data ~~point~~ points are restricted to a depth shallower than 20m. The dashed black line is the freezing temperature. Stronger opacity of the data points refers to a higher number of data.

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~~ solid lines are mixing lines ~~showing~~ indicating the water masses from the Bothnian Sea and Bothnian Bay which potentially 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 7) 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. Brine properties have been chosen according to our observations SA=15g kg^{-1} and CT=-0.78°C (freezing temperature). 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~~

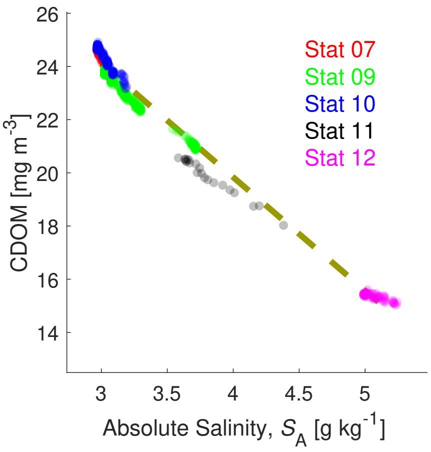


Figure 9. Salinity – CDOM diagram. The dashed line is the mixing line. Stronger opacity of the data points refers to a higher number of data. Data of station 7 are mostly covered by station 9 and 10 data.

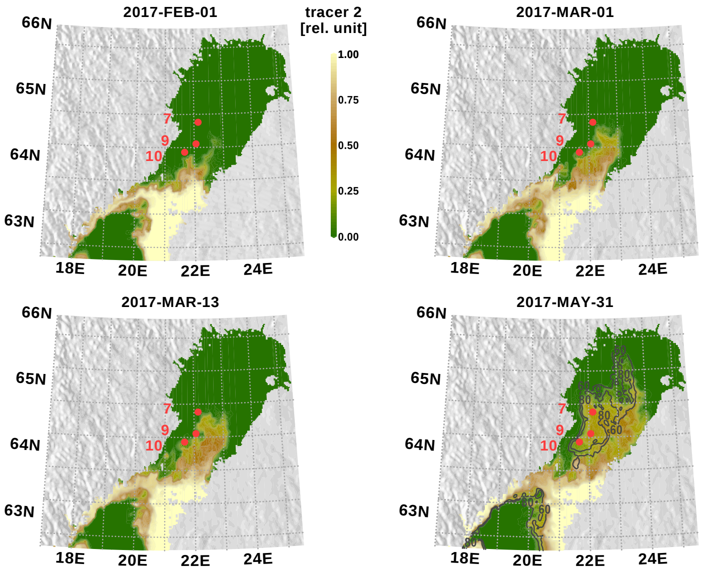
~~possibility is given by the gray dash-dotted mixing line in Fig. 8, assuming Bothnian Bay surface water was mixed with Bothnian Sea water. Apparently, much higher temperature (app. 1) in the Bothnian Sea would be necessary.~~

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). All water masses considered (oxygen saturated) are along the mixing line.

3.3 Model simulations

The propagation of Bothnian Sea surface tracer is shown in Fig. 10 as the surface tracer concentration just above the sea floor, i.e. former surface water already descended to the bottom. Surface water from the Bothnian Sea arrives at the area of our observations in mid-March. The snapshot from May 31st shows the areas which are ventilated until the end of the model simulation where the dense water plume arrives at the most northern deep parts of the basin.

In Fig.11, we show the time development of the surface tracer concentrations at station 9. A considerable concentration of Bothnian Sea surface water arrives around the 10th of March in the bottom water of station 9. Both surface tracer, from the Bothnian Bay and the Bothnian Sea, account for 50%–60% of the bottom water. The contribution of brine is less than 1% and negligible. The mean age of surface water is shown in the lower panel of Fig 11. In the beginning of March, it shows the age of the small amount of surface water arrived shortly after the simulation have been started. The mean age drops down by 20–25 days when the pulse of surface water (March 7th–10th) arrives. The last surface contact of Bothnian Sea water was about 35 days ago, i.e. around February 1st. At this time, surface water masses from the Bothnian Sea and Bothnian Bay have been mixed. The resulting density initiated a down-slope transport into the Bothnian Sea leaving the surface water.



2017-FEB-01

2017-MAR-01

2017-MAR-13

2017-MAY-31

Figure 10. Bothina Sea surface tracer concentration in the next to the bottom model layer. Red dots indicate the observation stations. In the fourth sub-figure, bathymetry contour lines for 60m and 80m depth are shown.

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. 7). 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~~ mechanisms 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.

The low temperature and the very high oxygen concentration (Fig. 7) 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 (magenta dots) and Bothnian Bay water hardly can result in the observed oxygen rich ~~,~~ and cold bottom water. Only a small portion of Bothnian Bay water in about ~~40~~40–50m depth (blue dots) shows the appropriate TS properties. However, assuming temperatures ~~in the Bothnian Sea~~ would be higher ~~, approximately about 1,~~ earlier in the winter season, 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.~~

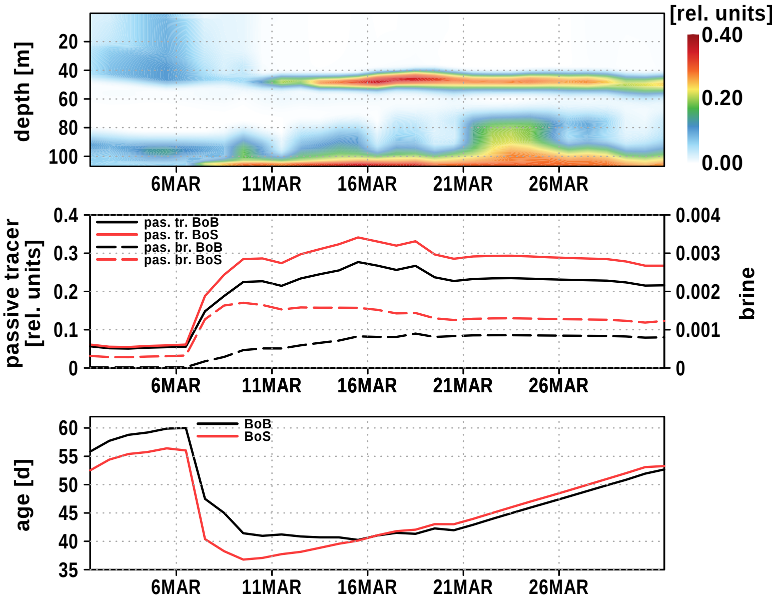


Figure 11. Time series of Bothina Sea and Bay surface tracer at station 9 (Fig. 3). The upper panel shows the vertical distribution of Bothnian Sea surface water; the middle panel shows the concentrations of Bothnian Sea (red) and Bay (black) surface water, and the concentration of brine (dashed, right y-axis) in the bottom water at station 9; the lower panel shows the mean age of Bothnian Sea and Bay surface water in the bottom water at station 9.

We show in Fig. 12 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 -0.5have 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).~~ as seen in our model simulation. The shown SST is an area average for the southern Bothnian Bay and the northern Bothnian Sea. In both areas, the SST simultaneously decreases and a suitable SST, forming the observed bottom water, can be found in the beginning of February.

~~There is hardly any situation where inflowing surface water from the Bothnian Sea shows a SST of about 1~~The model simulation with a passive tracer approach supports these findings. The majority of new bottom water is formed from surface water which starts to descent in the beginning of February.

However, app. 30% of simulated bottom was not in contact with the surface. This is also evident from the simulated temperature. It drops from 2.8°C ~~while at the same time in the Bothnian Bay the SST is close to the freezing temperature (-0.2~~to 1.6°C ~~). For the case that both mixing water masses are close to the temperature of the bottom water at station 9 (app. 0.3), a time window exists between February 18th and 22nd. However, we cannot say that during this time surface water from~~

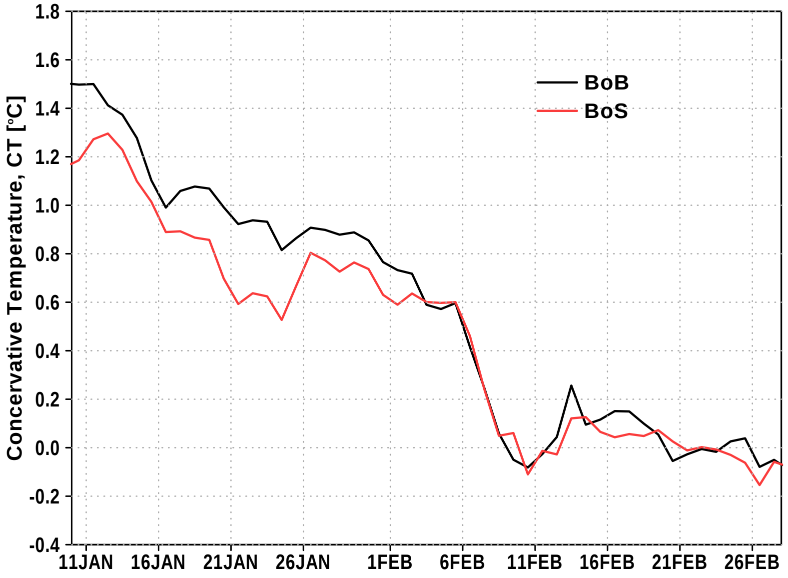


Figure 12. ~~Satellite derived sea surface temperature at 3 locations~~ Model SST in the southern Bothnian ~~Sea~~/Bay ~~in 2017. Location 1: 21.16E 63.75N, Location 2: 20.50E 63.15N, Location 3: 21.57E 63.91N. Data source: These data were provided by the Danish Meteorological Institute~~ (~~DMI~~black) and ~~GHRSST via marine~~the northern Bothnian Sea (red). ~~copernicus.eu. Note: Data gaps are due to sea ice cover.~~

~~the Bothnian Sea flowed into the Bothnian 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.~~ with the arrival of the new water mass and reflects that about one third is from older and warmer, intermediate or bottom water. The overestimation of entrainment is a known issue of z-coordinate models, especially for down flowing dense water plumes (Winton et al., 1998).

~~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/). At February 18th, warmerwater is crossing the Northern Quark and some Bothnian Sea water plumes may have entered the Bothnian Bay, shown by satellite derived SST in Fig. **??**. Average wind speed and direction over the Bothnian Sea. Data source: Deutscher Wetter Dienst (German Weather Service) (2019) Strong westerly wind in the Bothnian Sea area (Fig. **??**) has pushed waterto 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. **??**). 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 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 ($15.4\mathrm{g\,m^3}$) and Bothnian Bay ($24\mathrm{g\,m^3}$) result in a bottom water concentration in the Bothnian Bay of $20.6\mathrm{g\,m^3}$. This value is close to the observed value of $21\mathrm{g\,kg^{-1}}$ (Fig. 7).

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. These findings agree with our model simulations showing virtually no brine in the bottom water (Fig. 11).

~~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 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~~ Model simulations and observations show that bottom water ventilation in the Bothnian Sea is due to mixing of surface 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~~at the Northern Quark forming dense water which then initiate a down-flow cascade into the Bothnian Bay.

~~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, the sea ice thickness $\mathrm{H_I}$, and the Bothnian Bayarea A, we can write:~~

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

~~V_{bot} and S_{bot} are volume and salinity of the new bottom water, S_{w} is the surface water salinity, and S_{i} the bulk ice salinity. Using our observations S_{w}=3.0, S_{bot}=3.72, S_{i}=0.6and assuming a basin wide ice thickness of 0.2, the Bothnian Bay could be filled up to a depth of 93with 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. 7). Dividing the volumes in equation **??** by the area~~ Shapiro et al. (2003) developed a theory for dense water cascades at continental shelfs and derived a criterion discriminating between an accelerated event and a steady Ekman layer flow. The conditions for an accelerated cascade (Shapiro et al., 2003, eq. 9) are not fulfilled in the case of the Bothnian Bay, ~~one get an estimate of the thickness of the new water mass at the sea surface. Assuming again 0.2sea ice thickness, the new bottom water would have a vertical extent of 0.6. In areas shallower than the pycnocline, dense water can accumulate at the sea floor and form density driven plumes guided by topography~~thus the down-slope flow is rather a bottom boundary layer Ekman flow than an accelerated event.

~~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 (19deep, Fig. 3). In Fig. **??**, 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). 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 For the period 1985 until 2000, the bottom salinity in winter (blue in Fig. **??**) 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.~~ A density estimate based on our observed data show that the density gradient between Bothnian Bay bottom water and surface water at the Norther Quark vanishes if the SST exceeds 8°C. Therefore, a ventilation will occur in winter only.

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 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~~0.3°C) compared to the other two stations. We assume that this bottom water was formed due to a recent intrusion of former surface water. Complementing the observations, a numerical model experiment has been designed allowing to track different water masses.

~~Owing to the bottom water mass properties, brine rejection could have formed the bottom water~~ Observations, and especially CDOM data, exclude a mechanism where brine contributes to dense water formation. Also the model simulation gives no evidence for a contribution of brine. ~~Contrarily, CDOM measurements do not support this hypothesis. Also historical datado 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~~ The plausible ventilation mechanism is the inflow of Bothnian Sea surface water into the Bothnian Bay. We found a possible time for such an inflow ~~3~~ 5 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. A necessary horizontal density gradient establishes only for a low surface water temperature. Consequently, these ventilation events occur in the winter season. 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~~We observed the ventilation at one station only. 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.~~ the model simulation shows that the dense water plume progresses further northwards during spring and ventilates also the northernmost part. We are aware that our observations are a snapshot supported by numerical model simulations. Therefore, we are planning an extended campaign including moorings equipped with current meters. The model simulations are an excellent tool stimulating and guiding CTD and mooring stations.

Data availability. All sea ice and brine data are 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. Model simulation data are freely available from https://thredds-iow.io-warnemuende.de/thredds/c
THREDDS-Baltic_ref_2020-04-21-10.

Appendix A: Model assessment

In this section, we demonstrate the model performance for reproducing sea ice, temperature, and salinity in the northern Baltic Sea. Although the model run starts in 1948, we show the validation from 1990 to 2018, the last 30 years of the simulation. We skip the first 40 years, because the model was still drifting due to the long residence time of the Baltic Sea, especially in the northern parts.

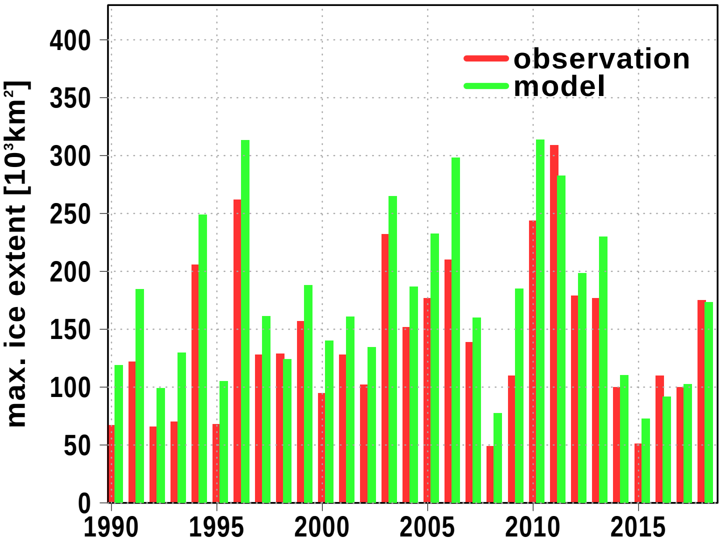


Figure A1. Simulated (green) and observed (red) maximum sea ice extend. Observations are obtained freely from https://en.ilmatieteenlaitos.fi/ice-winter-in-the-baltic-sea.

Figure A1 shows the annual maximum ice extent from observations (red bars) and from the model simulation (green bars). The variability is well reproduced by the model while in most years the extent is somewhat overestimated. In the model, we summed up all ice classes including frazil which might not always be part of the observations.

In the following figures, we show temperature and salinity data from two stations in the Bothnian Bay and in the Bothnian Sea, respectively. We focus on surface data (green) and data from close to the sea floor (blue). All observations are freely distributed by ICES (www.ices.dk). In Fig. A2, the locations of the two stations are shown.

Temperature and salinity are reasonable reproduced in the Bothnian Bay (F9). A weakness are the low bottom temperature events which are not reproduced well by the model. The reason is the overestimation of entrainment in z-coordinate model as discussed in section 4.

Salinity in the Bothnian Sea (SR5) bottom water is overestimated by app. 0.5$\mathrm{g\,kg^{-1}}$. Surface salinity and temperature show a reasonable good performance.

In summary, we assess that the model is able to reproduce the relevant processes sufficiently. The experiment with the passive tracers show that despite the enhanced entrainment also the ventilation of bottom water is reflected in the model.

Author contributions. TN and MM designed the experiment, TN designed and performed the model simulations, 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.

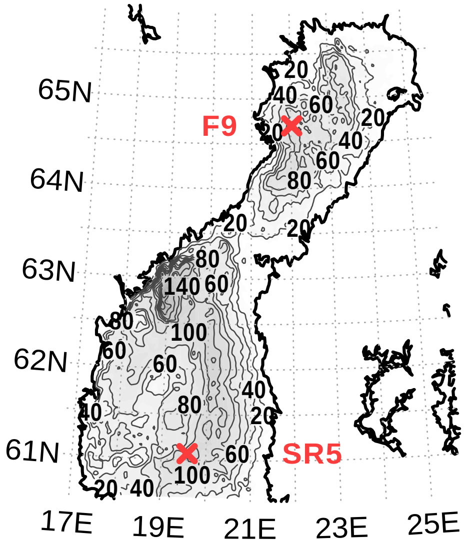


Figure A2. Location of the validation stations. The map was created using the software package GrADS 2.1.1.b0 (http://cola.gmu.edu/grads/), using published bathymetry data (Seifert et al., 2008).

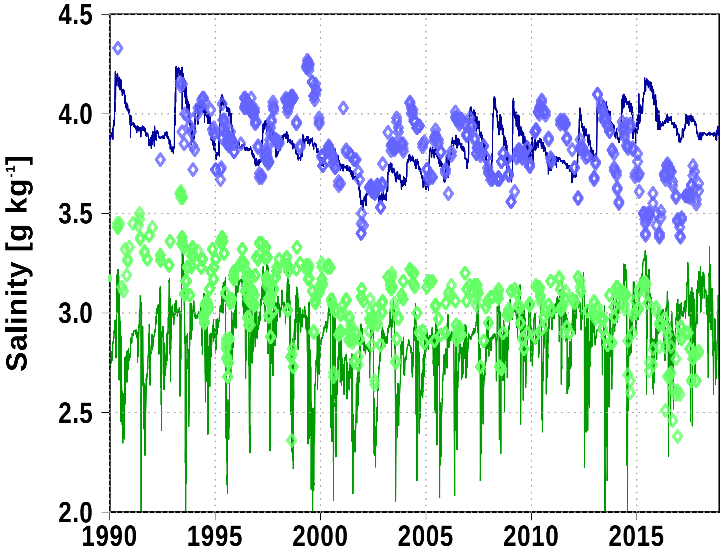


Figure A3. Surface (green) and bottom (blue) salinity at station F9. Solid line: Model, Diamonds: Observations (www.ices.dk).

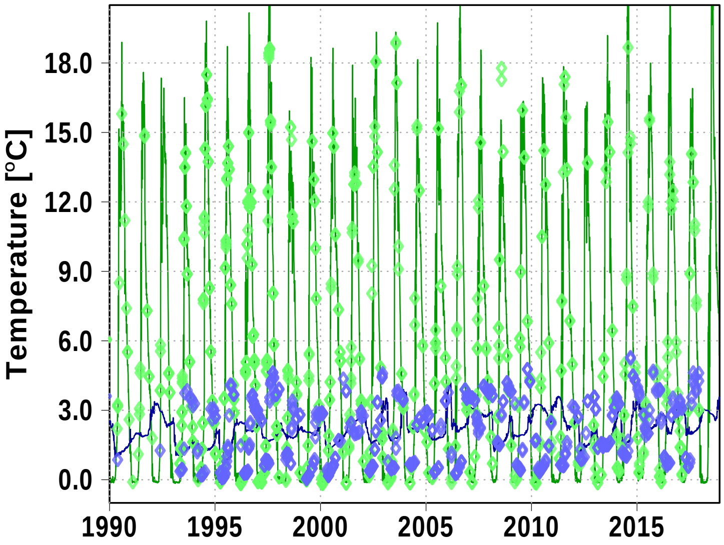


Figure A4. Surface (green) and bottom (blue) temperature at station F9. Solid line: Model, Diamonds: Observations (www.ices.dk).

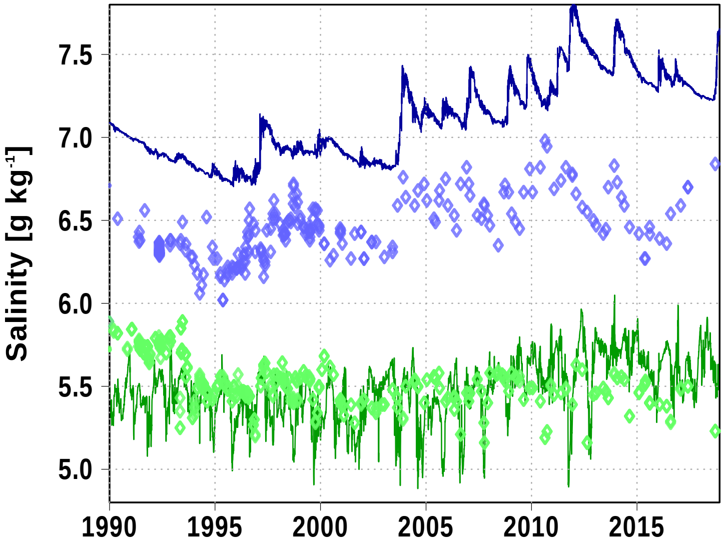


Figure A5. Surface (green) and bottom (blue) salinity at station SR5. Solid line: Model, Diamonds: Observations (www.ices.dk).

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

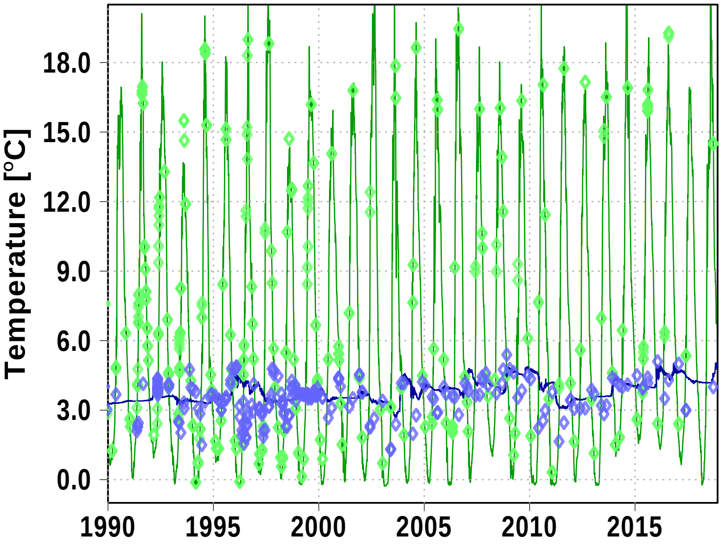


Figure A6. Surface (green) and bottom (blue) temperature at station SR5. Solid line: Model, Diamonds: Observations (www.ices.dk).

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References

Aagaard, K., Coachman, L., and Carmack, E.: On the halocline of the Arctic Ocean, Deep Sea Research Part A. Oceanographic Research Papers, 28, 529 – 545, https://doi.org/10.1016/0198-0149(81)90115-1, 1981.

Assur, A.: Composition of Sea Ice and its Tensile Strength, in: Arctic Sea Ice, pp. 106–138, U.S. National Academy of Science – National Research Council, Washington, D.C., 1958.

Baltic Icebreaking Management: Baltic Sea Icebreaking Report 2016-2017., Tech. rep., Baltic Icebreaking Management, http://baltice.org/app/static/pdf/BIM%20Report%2016-17.pdf, 2017.

Deutscher Wetter Dienst (German Weather Service): Operational weather forecasts, https://www.dwd.de/EN/research/weatherforecasting/num_modelling/01_num_weather_prediction_modells/icon_description.html?nn=484268, last accessed on 5 Mar. 2019, 2019.

Geyer, B. and Rockel, B.: coastDat-2 COSMO-CLM Atmospheric Reconstruction, https://doi.org/10.1594/WDCC/coastDat-2_COSMO-CLM, https://doi.org/10.1594/WDCC/coastDat-2_COSMO-CLM, 2013.

Golden, K. M., Ackley, S. F., and Lytle, V. I.: The Percolation Phase Transition in Sea Ice, Science, 282, 2238–2241, https://doi.org/10.1126/science.282.5397.2238, 1998.

Granskog, M., Kaartokallio, H., Kuosa, H., Thomas, D. N., and Vainio, J.: Sea ice in the Baltic Sea ? A review, Estuarine, Coastal and Shelf Science, 70, 145 – 160, https://doi.org/https://doi.org/10.1016/j.ecss.2006.06.001, http://www.sciencedirect.com/science/article/pii/S0272771406002538, applying the Ecohydrology approach to the Guadiana estuary and coastal areas: lessons learned from dam impacted ecosystems, 2006.

Granskog, M. A., Kaartokallio, H., Kuosa, H., Thomas, D. N., Ehn, J., and Sonninen, E.: Scales of horizontal patchiness in chlorophyll a, chemical and physical properties of landfast sea ice in the Gulf of Finland (Baltic Sea), Polar Biology, 28, 276–283, https://doi.org/10.1007/s00300-004-0690-5, 2005.

Griffies, S. M.: Fundamentals of Ocean Climate Models, Princeton University Press, Princeton, NJ, 2004.

Harvey, E. T., Kratzer, S., and Andersson, A.: Relationships between colored dissolved organic matter and dissolved organic carbon in different coastal gradients of the Baltic Sea, AMBIO, 44, 392–401, https://doi.org/10.1007/s13280-015-0658-4, 2015.

ICES: Dataset on Ocean Hydrography. The International Council for the Exploration of the Sea, Copenhagen. 2018, http://www.ices.dk/, last accessed on 2019-05-08.

ICO, SCOR, and IAPSO: The international thermodynamic equation of seawater — 2010: Calculation and use of thermodynamic properties., Tech. Rep. 56, Intergovernmental Oceanographic Commission, Manuals and Guides, 2010.

Ivanov, V., Shapiro, G., Huthnance, J., Aleynik, D., and Golovin, P.: Cascades of dense water around the world ocean, Progress in Oceanography, 60, 47 – 98, https://doi.org/https://doi.org/10.1016/j.pocean.2003.12.002, http://www.sciencedirect.com/science/article/pii/S0079661104000035, 2004.

Jerlov, N., ed.: Marine Optics, vol. 14 of *Elsevier Oceanography Series*, Elsevier, https://doi.org/10.1016/S0422-9894(08)70789-X, 1976.

Kabel, K., Moros, M., Porsche, C., Neumann, T., Adolphi, F., Andersen, T. J., Siegel, H., Gerth, M., Leipe, T., Jansen, E., and Sinninghe Damsté, J. S.: Impact of climate change on the Baltic Sea ecosystem over the past 1,000 years, Nature Climate Change, https://doi.org/10.1038/nclimate1595, 2012.

Kirk, J. T.: Light and Photosynthesis in Aquatic Ecosystems, Cambridge University Press, New York, 2nd edn., 1994.

Lass, H.-U. and Matthäus, W.: General Oceanography of the Baltic Sea, chap. 2, pp. 5–43, Wiley-Blackwell, https://doi.org/10.1002/9780470283134.ch2, 2008.

Marmefelt, E. and Omstedt, A.: Deep water properties in the Gulf of Bothnia, Continental Shelf Research, 13, 169 – 187, https://doi.org/10.1016/0278-4343(93)90104-6, 1993.

Meiners, K., Fehling, J., Granskog, M. A., and Spindler, M.: Abundance, biomass and composition of biota in Baltic sea ice and underlying water (March 2000), Polar Biology, 25, 761–770, https://doi.org/10.1007/s00300-002-0403-x, 2002.

Mohrholz, V.: Major Baltic Inflow Statistics ? Revised, Frontiers in Marine Science, 5, 384, https://doi.org/10.3389/fmars.2018.00384, https://www.frontiersin.org/article/10.3389/fmars.2018.00384, 2018.

Morison, J. H. and McPhee, M. G.: Lead convection measured with an autonomous underwater vehicle, Journal of Geophysical Research: Oceans, 103, 3257–3281, https://doi.org/10.1029/97JC02264, 1998.

Moros, M., Kotilainen, A. T., Snowball, I., Neumann, T., Perner, K., Meier, H. M., Leipe, T., Zillén, L., Sinninghe Damsté, J. S., and Schneider, R.: Is deep-water formation in the Baltic Sea a key to understanding seabed dynamics and ventilation changes over the past 7,000 years?, Quaternary International, https://doi.org/https://doi.org/10.1016/j.quaint.2020.03.031, http://www.sciencedirect.com/science/article/pii/S1040618220301257, 2020.

Müller, S., Vähätalo, A. V., Granskog, M. A., Autio, R., and Kaartokallio, H.: Behaviour of dissolved organic matter during formation of natural and artificially grown Baltic Sea ice, Annals of Glaciology, 52, 233–241, https://doi.org/10.3189/172756411795931886, 2011.

Müller, S., Vähätalo, A. V., Stedmon, C. A., Granskog, M. A., Norman, L., Aslam, S. N., Underwood, G. J., Dieckmann, G. S., and Thomas, D. N.: Selective incorporation of dissolved organic matter (DOM) during sea ice formation, Marine Chemistry, 155, 148–157, https://doi.org/10.1016/j.marchem.2013.06.008, 2013.

Neumann, T.: Climate-change effects on the Baltic Sea ecosystem: A model study, Journal of Marine Systems, 81, 213–224, https://doi.org/10.1016/j.jmarsys.2009.12.001, 2010.

Neumann, T., Siegel, H., and Gerth, M.: A new radiation model for Baltic Sea ecosystem modelling, Journal of Marine Systems, 152, 83–91, https://doi.org/http://dx.doi.org/10.1016/j.jmarsys.2015.08.001, http://www.sciencedirect.com/science/article/pii/S0924796315001426, 2015.

Nguyen, A. T., Menemenlis, D., and Kwok, R.: Improved modeling of the Arctic halocline with a subgrid-scale brine rejection parameterization, Journal of Geophysical Research: Oceans, 114, https://doi.org/10.1029/2008JC005121, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2008JC005121, 2009.

Peterson, A. K.: Observations of brine plumes below melting Arctic sea ice, Ocean Science, 14, 127–138, https://doi.org/10.5194/os-14-127-2018, 2018.

Raateoja, M.: Deep-water oxygen conditions in the Bothnian Sea, Boreal Env. Res., 18, 235–249, 2013.

Seifert, T., Tauber, F., and Kayser, B.: Digital topography of the Baltic Sea, https://www.io-warnemuende.de/topography-of-the-baltic-sea.html, last accessed on 2019-07-15, 2008.

Shapiro, G. I., Huthnance, J. M., and Ivanov, V. V.: Dense water cascading off the continental shelf, Journal of Geophysical Research: Oceans, 108, https://doi.org/10.1029/2002JC001610, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002JC001610, 2003.

Skogseth, R., Smedsrud, L. H., Nilsen, F., and Fer, I.: Observations of hydrography and downflow of brine-enriched shelf water in the Storfjorden polynya, Svalbard, Journal of Geophysical Research: Oceans, 113, https://doi.org/10.1029/2007JC004452, 2008.

Smith, D. C. and Morison, J. H.: Nonhydrostatic haline convection under leads in sea ice, Journal of Geophysical Research: Oceans, 103, 3233–3247, https://doi.org/10.1029/97JC02262, 1998.

Stigebrandt, A.: A Model for the Vertical Circulation of the Baltic Deep Water, Journal of Physical Oceanography, 17, 1772–1785, https://doi.org/10.1175/1520-0485(1987)017<1772:AMFTVC>2.0.CO;2, http://dx.doi.org/10.1175/1520-0485(1987)017<1772:AMFTVC>2.0.CO;2, 1987.

Winton, M.: A Reformulated Three-Layer Sea Ice Model, Journal of Atmospheric and Oceanic Technology, 17, 525–531, https://doi.org/10.1175/1520-0426(2000)017<0525:ARTLSI>2.0.CO;2, https://doi.org/10.1175/1520-0426(2000)017<0525:ARTLSI>2.0.CO;2, 2000.

Winton, M., Hallberg, R., and Gnanadesikan, A.: Simulation of Density-Driven Frictional Downslope Flow in Z-Coordinate Ocean Models, Journal of Physical Oceanography, 28, 2163–2174, https://doi.org/10.1175/1520-0485(1998)028<2163:SODDFD>2.0.CO;2, https://doi.org/10.1175/1520-0485(1998)028<2163:SODDFD>2.0.CO;2, 1998.