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Hydrographic-hydrochemical assessment of the Baltic Sea 2023

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Zusammenfassung

Die Arbeit beschreibt die hydrographisch-hydrochemischen Bedingungen in der westlichen und zentralen Ostsee im Jahr 2023. Basierend auf den meteorologischen Verhältnissen werden die horizontalen und vertikalen Verteilungsmuster von Temperatur, Salzgehalt, Sauerstoff/Schwefelwasserstoff und Nährstoffen mit saisonaler Auflösung dargestellt.

Der Winter 2022/2023 belegt mit einer Kältesumme von 30,8 Kd, gemessen in Warnemünde, den 15. Platz der wärmsten Winter der Datenreihe seit dem Jahr 1948. Die Wärmesumme des Sommers 2023 ist mit 288,7 Kd nur knapp über dem Vorjahr (281,4 Kd), jedoch deutlich über dem Mittelwert von 163,0 Kd.

Die seit 2017 andauernde Serie von Jahren mit nur schwachen Einstromereignissen wurde im Jahr 2023 endlich unterbrochen. Im Dezember ereignete sich um die Weihnachtsfesttage herum ein Salzwassereinstrom, der nach MOHRHOLZ (2018) als „Major Baltic Inflow“ (MBI) mittlerer Intensität klassifiziert werden konnte und etwa 1,7 Gt salzreiches Wasser (>15 g kg^{-1}) in das Tiefenwasser des Arkona Beckens transportierte.

Durch die fortschreitende Akkumulierung von Schwefelwasserstoff im Tiefenwasser der Gotlandsee setzte sich die Intensivierung des Sauerstoffmangels und seiner Begleiterscheinungen in 2023 grundsätzlich fort. Das erhöhte Sauerstoffdefizit wurde wahrscheinlich durch die anhaltende Eutrophierung und die produzierten und anschließend remineralisierten großen Mengen an Biomasse verursacht. An der Station Gotlandtief nahm die der Schwefelwasserstoff äquivalenten Sauerstoffkonzentration seit 2019 auf -317 µmol l^{-1} und am Fårötief auf -171 µmol l^{-1} Sauerstoff im Jahr 2023 in den entsprechenden Tiefenwasser Referenztiefen ab.

Das zum Teil kühle und stürmische Wetter im Sommer verhinderte weitgehend einen starken saisonalen Sauerstoffmangel im Bodenwasser der flachen Bereiche der Ostsee. Darüber hinaus strömte kaltes Wasser eines kleineren barotropen Einstroms aus dem Dezember 2022 erst in die Arkonasee und dann überfloss und mischte sich der Wasserkörper im März in das bereits sauerstoffangereicherte warme Wasser in der zentralen Bornholmsee mit einer resultierenden Sauerstoffkonzentration von 145-255 µmol l^{-1}. Ein einzelnes Wasserpaket mit diesem warmen sauerstoffangereicherten Wasser von immerhin noch 30 µmol l^{-1} Sauerstoff erreichte die südliche Gotlandsee und strömte den Talweg weiter abwärts bis auf etwa 120 m Tiefe.

Die Winter Nitratkonzentrationen im Oberflächenwasser von nun etwa 2.7 µmol l^{-1} auf den Stationen Gotlandtief und Bornholmtief lagen wieder unter dem Vorjahreswert. Die Frühjahrsblüte 2023 endete am Bornholmtief etwa Ende März und an der Station Gotlandtief Ende April. Eine deutlich erkennbare Erhöhung der Nitratkonzentration erfolgte dann am Bornholmtief nicht vor Mitte November und am Gotlandtief erst Ende November. Zu der Zeit hatte die Abkühlung des Oberflächenwassers etwa 10 °C am Bornholmtief und 12 °C am Gotlandtief erreicht, was die windgetriebene Durchmischung bei herbstlichem Wetter und damit den Nachschub der Nährstoffe aus tieferem Wasser ermöglichte. Die räumliche Verteilung des Verhältnisses von gelöstem anorganischem Stickstoff zu Phosphat war ähnlich wie im Vorjahr und zeigte wieder einmal die deutliche Beschränkung der Nitratverfügbarkeit für die Frühjahrsblüte und die deutliche Begünstigung der Cyanobakterien gegenüber

Primärproduzenten, die auf Nitrat angewiesen sind. Schon stark im Tiefenwasser angereichtes Phosphat am Gotlandtief wies eine erneute Erhöhung der Konzentration auf 6.2 µmol l^{-1} in der Referenztiefe auf, sowie auf 4.3 µmol l^{-1} am Karlsötief auf. Demgegenüber wurde an den Stationen Fårötief und Landsorttief etwa die gleichen Jahresmittelwerte von 4.7 µmol l^{-1} und 4.1 µmol l^{-1} Phosphat, wie im Vorjahr gemessen. Die Nitratkonzentration lag im Tiefenwasser der Gotlandsee weitgehend unter der Nachweisgrenze, was an den vorherrschend euxinischen (sulfidischen) Bedingungen lag, die eine Remineralisierung von organischem Material bis zum Nitrat verhindern, stattdessen wurde Ammonium gebildet. Vergleichbar mit dem Phosphat, wurde eine fortgesetzte Akkumulation von Ammonium im Tiefenwasser der Gotlandsee beobachtet. Eine besonders hohe Anreicherung von 35.4 µmol l^{-1} Ammonium wurde im Gotlandtief, von immerhin 16.9 µmol l^{-1} im Fårötief und von 12.8 µmol l^{-1} am Landsorttief gemessen. Das Karlsötief wies eine ähnliche Konzentration wie im Vorjahr von 15.9 µmol l^{-1} Ammonium auf.

Im Gegensatz zu Phosphat, könnte die winterliche Nitratkonzentration im Oberflächenwasser die Zielkonzentration von HELCOM immer mal wieder erreichen, aber eine permanente Unterschreitung der Grenze erscheint in nächste Zukunft unwahrscheinlich. Dabei muss berücksichtigt werden, dass das Tiefenwasser der zentralen Ostseebecken gegenwärtig aufgrund der euxinischen (sulfidischen) Bedingungen eine starke Nitratsenke darstellt, so dass ein Teil der gemessenen Nitratabnahme nicht nur auf Eintragsreduktionen zurückgeführt werden kann. Wieweit die Transporte von akkumuliertem Ammonium nun aus dem Tiefenwasser zunehmen, bleibt unklar. Für Phosphat wird das unterschreiten der angestrebten Grenzwerte voraussichtlich noch mehre Dekaden dauern.

Oberflächenseewasserproben wurden in Untersuchungsgebieten von der Kieler Bucht bis zur Gotlandsee mittels Transektbeprobung während der Expedition EMB311 genommen. Diese wurden auf die chlorierten Kohlenwasserstoffe Dichlordiphenyltrichlorethan (*o,p*‘-DDT, *p,p*‘-DDT) und die Metabolite *p,p*‘-DDE und *p,p*‘-DDD, polychlorierte Biphenyle (PCB_{ICES}), Hexachlorbenzol (HCB), Heptachlor (HEP) und den Metaboliten Heptachlorepoxid (HEPEP) sowie polyzyklische aromatische Kohlenwasserstoffe (U.S. EPA PAH) untersucht. Darüber hinaus wurden im Untersuchungsgebiet Oberflächenseewasserproben mittels Glaskugelschöpfer genommen und auf die α, ß und γ Isomere des Hexachlorcyclohexans (ΣHCH) untersucht.

Die ermittelten Konzentrationen für DDT und Metabolite (ΣDDT_{sum}) lagen im Bereich von 2,53 pg l^{-1} bis 13,08 pg l^{-1}, wobei die höchste Konzentration für die Pommersche Bucht gefunden wurde. Niedrigere Konzentrationen von *p,p*‘-DDT gegenüber dem langlebigen Abbauprodukt *p,p*‘-DDE deuten auf keine aktuellen Einträge von DDT hin.

Die Konzentrationen von PCB_{ICES} und HCB lagen zwischen 1,73 pg l^{-1} und 8,52 pg l^{-1} ΣPCB_{SUM} sowie zwischen 4.30 pg l^{-1} und 11.13 pg l^{-1} HCB_{SUM}. Die höchste Konzentration von ΣPCB_{SUM} wurde für die Mecklenburger Bucht (8,52 pg l^{-1}) verzeichnet, wohingegen die höchsten HCB-Konzentrationen im südlichen Teil der östlichen Gotlandsee (11,13 pg l^{-1}) nachgewiesen wurden. HEPEP wurde in der gelösten Phase der Oberflächenseewasserproben im Bereich von 0,16 pg l^{-1} bis 1,05 pg l^{-1} detektiert. In 2023 konnte im Untersuchungsgebiet Mecklenburger Bucht auch HEP in der gelösten Phase mit 0,09 pg l^{-1} nachgewiesen werden.

Die Belastung des Oberflächenwassers mit PAH lag im Bereich von 1293 pg l^{-1} bis 5150 pg l^{-1} ΣPAH_{sum} mit der höchsten Konzentration in der Pommerschen Bucht. Die meisten der in 2023 ermittelten Konzentrationen für ΣPAH_{sum} lagen unter dem 25. Perzentil der im Untersuchungszeitraum (2003 - 2023) ermittelten Daten.

Die ermittelten Konzentrationen für ΣHCH lagen im Bereich von 108 pg l^{-1} in der Kieler Bucht (N3) bis 161 pg l^{-1} in der Arkonasee (K7) mit ß-HCH als dem vorherrschenden Isomer. Die Langzeitanalyse der HCH-Isomere an der Station K4 (Arkonasee) mit Daten zurückliegend bis zum Jahr 1975 zeigt anhaltend abnehmende Konzentrationen im Oberflächenwasser und deutet auf keine aktuellen HCH-Einträge.

Die Bewertung der ermittelten Daten erfolgte auf Grundlage der Umweltqualitätsnormen (UQN) der Wasserrahmenrichtlinie. Alle für HEP und HEPEP ermittelten Konzentrationen überschreiten die Jahresdurchschnitts-UQN von 0.01 pg l^{-1}. Für die Mecklenburger und Pommersche Bucht lagen die ermittelten Konzentrationen für die hochmolekularen PAH BBF, BGHIP und ICDP über der Jahresdurchschnitts-UQN von 0.00017 pg l^{-1}.

Summary

The article summarizes the hydrographic-hydrochemical conditions in the western and central Baltic Sea in 2023. Based on the meteorological conditions, the horizontal and vertical distribution of temperature, salinity, oxygen/hydrogen sulphide and nutrients are described on a seasonal scale.

A “cold sum” of 30.8 Kd was recorded for wintertime 2022/2023 at station Warnemünde. It is classified as a mild winter on 15th position of warm winters over the past 75 years (1948-2023). The summer “heat sum” of 288.7 Kd is far above the long-term average of 163.0 Kd and above the previous year 2022 of 281.4 Kd.

In the course of the year 2023, the series of years (2017-2022) showing weak inflow activity into Baltic Sea was interrupted. During December occurred around Christmas intensified inflow activity, which is classified as midsized Major Baltic Inflow (MBI) event after MOHRHOLZ (2018) and imported a salt mass of 1.7 Gt (salinity >15 g kg^{-1}) into the deep water of the Arkona Basin.

By ongoing accumulation of hydrogen sulphide in deep water of the Gotland Sea, the intensifying of the oxygen deficit and accompanying symptoms basically continued in 2023. The increase of the oxygen deficit is caused by current eutrophication and produced and subsequently remineralized large amounts of biomass. At Gotland Deep station, the decline of oxygen continued since 2019 and showed an accumulation of hydrogen sulphide equivalent of -317 µmol l^{-1} oxygen and at Fårö Deep station of -171 µmol l^{-1} oxygen at respective deep water reference depths in 2023.

The partly cool and stormy weather in summer 2023 hindered a strong seasonal oxygen deficit in bottom water of shallow Baltic Sea areas. Moreover, cold water from a minor barotropic inflow event of December 2022 entered the Arkona Sea and surpassed and entrained the oxygen bearing warm water in the centre of the Bornholm Sea that resulted in an elevated oxygen concentration of 145-255 µmol l^{-1} in March. An isolated parcel of the warm oxygenated water of still 30 µmol l^{-1} oxygen in the southern Gotland Sea moved further down the Thalweg until a depth of about 120 m.

The winter surface water nitrate concentration of 2.7 µmol l^{-1} at Gotland Deep and at Bornholm Deep stations was measured in 2023 again below the values of previous year. The spring bloom in 2023 likely ended in the central Bornholm Sea end of March, and at the Gotland Deep station end of April. A significant replenishment of nitrate in the surface water did not take place at the Bornholm Deep station before mid-November and at Gotland Deep site end of November. At that time, cooling to about 10 °C at the Bornholm Deep site and 12 °C at the Gotland Deep station enabled wind induced mixing in autumn weather conditions and a supply of nutrients from deeper layers. The distribution pattern of the winter dissolved inorganic nitrogen versus phosphate ratio was similar to the situation in the last year and confirmed again in 2023 that nitrogen was a clearly limiting factor in the Baltic Proper, giving diazotrophic cyanobacteria an advantage compared to primary producers that depend on nitrate. In the Gotland Sea deep water strongly accumulated phosphate increased further to a concentration of 6.2 µmol l^{-1} in the Gotland Deep reference depths and to 4.3 µmol l^{-1} at the Karlsö Deep, whereas at Fårö Deep and Landsort Deep stations almost the same annual average phosphate concentration of 4.7 µmol l^{-1}

and 4.1 µmol l^{-1} as last year, was determined. Nitrate was mostly below the detection limit in deep water, which is caused by euxinic (sulphidic) conditions that prevent mineralization of organic matter to nitrate, and instead ammonium is formed. Similarly to phosphate, ongoing accumulation of ammonium in deep water was recorded for Gotland Sea deep water. In the Gotland Deep an extremely high ammonium concentration of 35.4 µmol l^{-1}, at Fårö Deep ammonium increased to 16.9 µmol l^{-1}, at Landsort Deep to 12.8 µmol l^{-1} and on Karlsö Deep a similar ammonium concentration as last year of 15.9 µmol l^{-1} were measured.

In contrast to phosphate, the nitrate winter surface water concentration may reach the HELCOM target values in certain years, but a permanent fulfilment appears unlikely in the near future. It should be noted that the deep water of central basins constituted a strong nitrate sink, because of the current intense euxinia. Thus a certain nitrate decline might not indicate the input reductions alone. However, the amount of a potential contribution of ammonium supply from deep water remains unknown. For phosphate very likely it may need some more decades to reach the targets that were aimed.

Surface seawater samples were obtained in study areas from Kiel Bight to the Gotland Sea by transect sampling during the expedition EMB311. These were analyzed for the chlorinated hydrocarbons dichlorodiphenyltrichloroethane (*o,p'*-DDT, *p,p'*-DDT) and the metabolites *p,p'*-DDE and *p,p'*-DDD, polychlorinated biphenyls (PCB_{ICES}), hexachlorobenzene (HCB), heptachlor (HEP) and the metabolite heptachlor epoxide (HEPEP) as well as polycyclic aromatic hydrocarbons (U.S. EPA PAH). In addition, surface seawater samples were taken using a spherical glass sampler and analyzed for the α, ß and γ isomers of hexachlorocyclohexane (ΣHCH).

Concentrations determined for DDT and metabolites (ΣDDT_{sum}) ranged from 2.53 pg l^{-1} to 13.08 pg l^{-1}, with the highest concentration found for the Pomeranian Bight. Lower concentrations of *p,p'*-DDT compared to the long-lived degradation product *p,p'*-DDE indicate no recent inputs of DDT.

Concentrations of PCB_{ICES} and HCB ranged from 1.73 pg l^{-1} to 8.52 pg l^{-1} ΣPCB_{SUM} and from 4.30 pg l^{-1} to 11.13 pg l^{-1} HCB_{SUM}. The highest concentration of ΣPCB_{SUM} was determined for the area Mecklenburg Bight (8.52 pg l^{-1}), whereas the highest HCB concentration was detected in the southern part of the eastern Gotland Sea (11.13 pg l^{-1}). HEPEP was detected in the dissolved phase of the surface seawater samples ranging from 0.16 to 1.05 pg l^{-1}. In 2023 also dissolved HEP was detected with 0.09 pg l^{-1} in the Mecklenburg Bight study area.

Obtained concentrations for PAH ranged from 1293 pg l^{-1} to 5150 pg l^{-1} ΣPAH_{sum} with the highest concentration found for the area Pomeranian Bight. Most ΣPAH_{sum} data observed in 2023 were below the 25th percentile of the data obtained within the investigated period (2003 – 2023).

ΣHCH concentrations ranged from 108 pg l^{-1} at Kiel Bight (N3) to 161 pg l^{-1} in the Arkona Sea (K7). The predominant isomer was ß-HCH. The long term analysis at station K4 (Arkona Sea) with data back to the year 1975 shows continuously reducing concentrations of ΣHCH which indicates no recent HCH inputs.

The assessment of the obtained data was based on the environmental quality standards (EQS) of the Water Framework Directive. All concentrations determined for HEP and HEPEP exceeded the annual average EQS of 0.01 pg l^{-1}. Determined concentrations for the high molecular weight PAHs BBF, BGHIP and ICDP were above the annual average EQS of 0.00017 pg l^{-1} in the areas Mecklenburg and Pomeranian Bight.

1 Introduction

This assessment of hydrographic and hydrochemical conditions in the Baltic Sea in 2023 has partially been produced on the basis of the Baltic Sea Monitoring Programme that the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) undertakes on behalf of the Federal Maritime and Hydrographic Agency, Hamburg and Rostock (BSH). Within the scope of an administrative agreement, the German contribution to the Helsinki Commission's (HELCOM) monitoring programme (COMBINE) for the protection of the marine environment of the Baltic Sea has been devolved to IOW. It basically covers Germany's Exclusive Economic Zone. Beyond these borders, the IOW is running an observation programme on its own account in order to obtain and maintain long-term data series and to enable analyses of the conditions in the Baltic Sea's central basins, which play a decisive role in the overall health of the sea.

The combination of both programmes leads to a yearly description of the water exchange between the North Sea and the Baltic Sea, the hydrographic and hydrochemical conditions in the study area, their temporal and spatial variations, as well as the investigation and identification of long-term trends.

Five routine monitoring cruises are undertaken each year covering all four seasons. The data obtained during these cruises, as well as results from other research activities by IOW, form the basis of this assessment. Selected data from other research institutions, especially the Swedish Meteorological and Hydrological Institute (SMHI) and the Maritime Office of the Polish Institute of Meteorology and Water Management (IMGW), are also included in the assessment.

HELCOM guidelines for monitoring in the Baltic Sea form the basis of the routine hydrographical and hydrochemical monitoring programme within its COMBINE Programme (HELCOM 2017). The five monitoring cruises in February, March, May, August and November were performed by RV Elisabeth Mann Borgese. Details about water sampling, investigated parameters, sampling techniques and their accuracy are given in NEHRING et al. (1993, 1995).

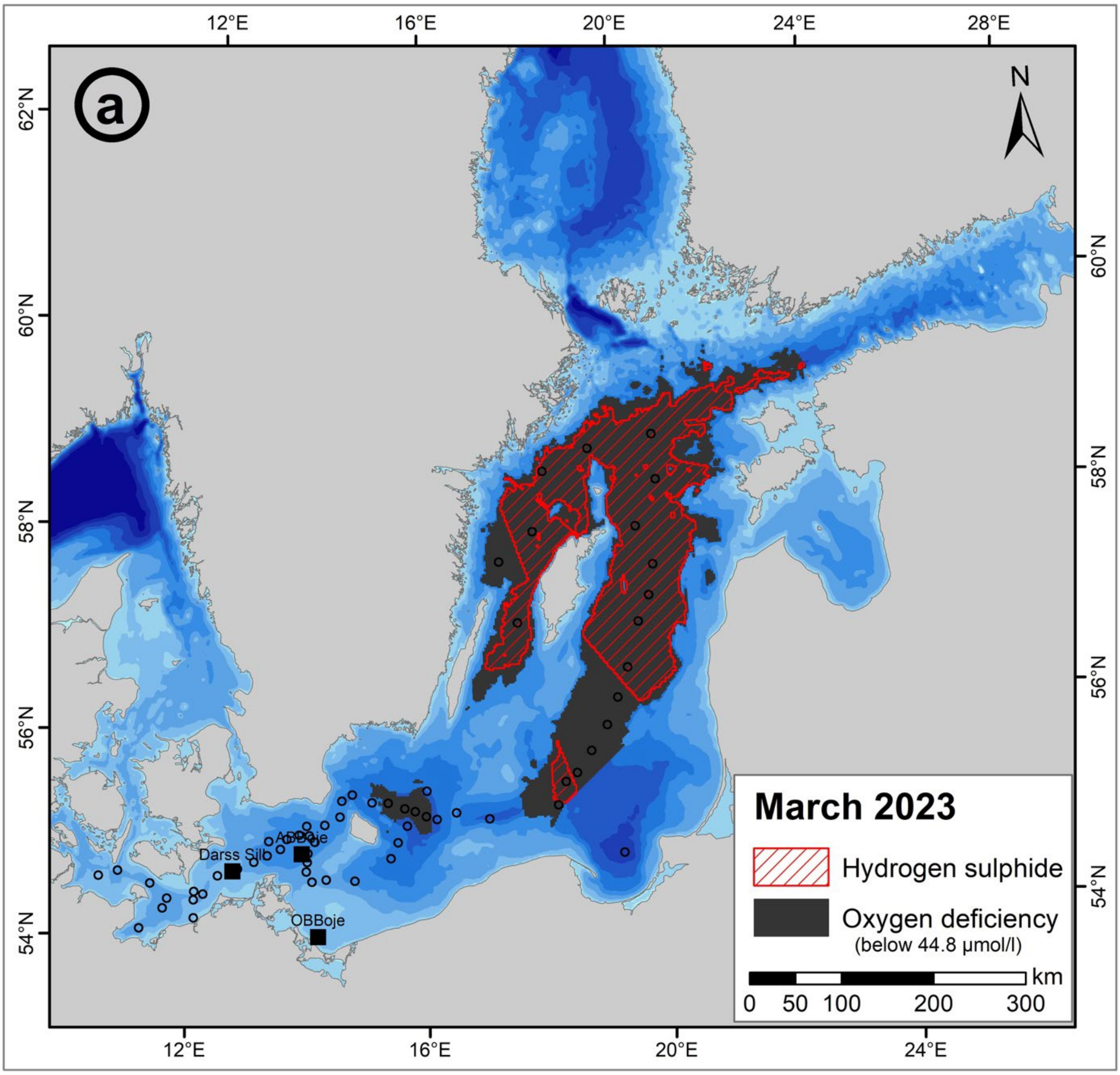
Ship-based investigations were supplemented by measurements at three autonomous stations within the German MARNET environmental monitoring network, the ARKONA BASIN (AB), the DARSS SILL (DS) station and the ODER BANK (OB) station. At December 12th 2022 the autonoumous measuring pile DARSS SILL was deployed again after its longer maintenance period in 2021-2022, but fully technical equipped and went again in operation since February 28th 2023. In wintertime 2022/23 the Oder Bank bouy was not taken out of service like usual in wintertime. As in previous years, in 2023 a second system of a new buoy construction more resistant against damages caused by ice was operated in parallel at the Oder Bank position, to have a longer test period for data evaluation and technical approval.

Besides meteorological parameters at these stations, water temperature and salinity as well as oxygen concentrations were measured at different depths:

AB:	8 horizons T + S	+	2 horizons O_2
DS:	6 horizons T + S	+	2 horizons O_2
OB:	2 horizons T + S	+	2 horizons O_2

All data measured at the MARNET stations are transmitted via METEOSAT to the BSH database as hourly means of six measurements (KRÜGER et al. 1998, KRÜGER 2000). An acoustic doppler current profiler (ADCP) records current speeds and directions at AB and DS. The ADCP arrays are located on the seabed in some two hundred metres distance from the main stations and protected by a trawl-resistant bottom mount mooring. They are operated in real time: via an hourly acoustic data link, they send their readings to the main station for storage and satellite transmission. For quality assurance and service purposes, data stored by the devices itself are read retrospectively during maintenance measures at the station once or twice a year.

As a general overview of the state of the Baltic Sea Fig. 1 shows the recent hypoxic to euxinic conditions. Oxygen deficiency is one of the major factors influencing the Baltic Sea ecosystem. The conditions in winter-spring and summer are shown in this map, visualising the development during the year 2023. A large extend of bottom water in the deep basins is influenced by hypoxia (black dotted areas). The situation is more or less stagnant comparing the winter to spring situation (March) with summer measurements in August at the eastern, northern and western Gotland basin, but the situation worsened at the Slupsk Channel and Bornholm basin with a spreading of hypoxic area as well as hydrogen sulphide in summertime (Fig. 1b).



a
March 2023
Hydrogen sulphide
Oxygen deficiency
(below 44.8 µmol/l)
km
0 50 100 200 300
N
Darss Sill
ARBoje
OBBoje
12°E
16°E
20°E
24°E
28°E
54°N
56°N
58°N
60°N
62°N

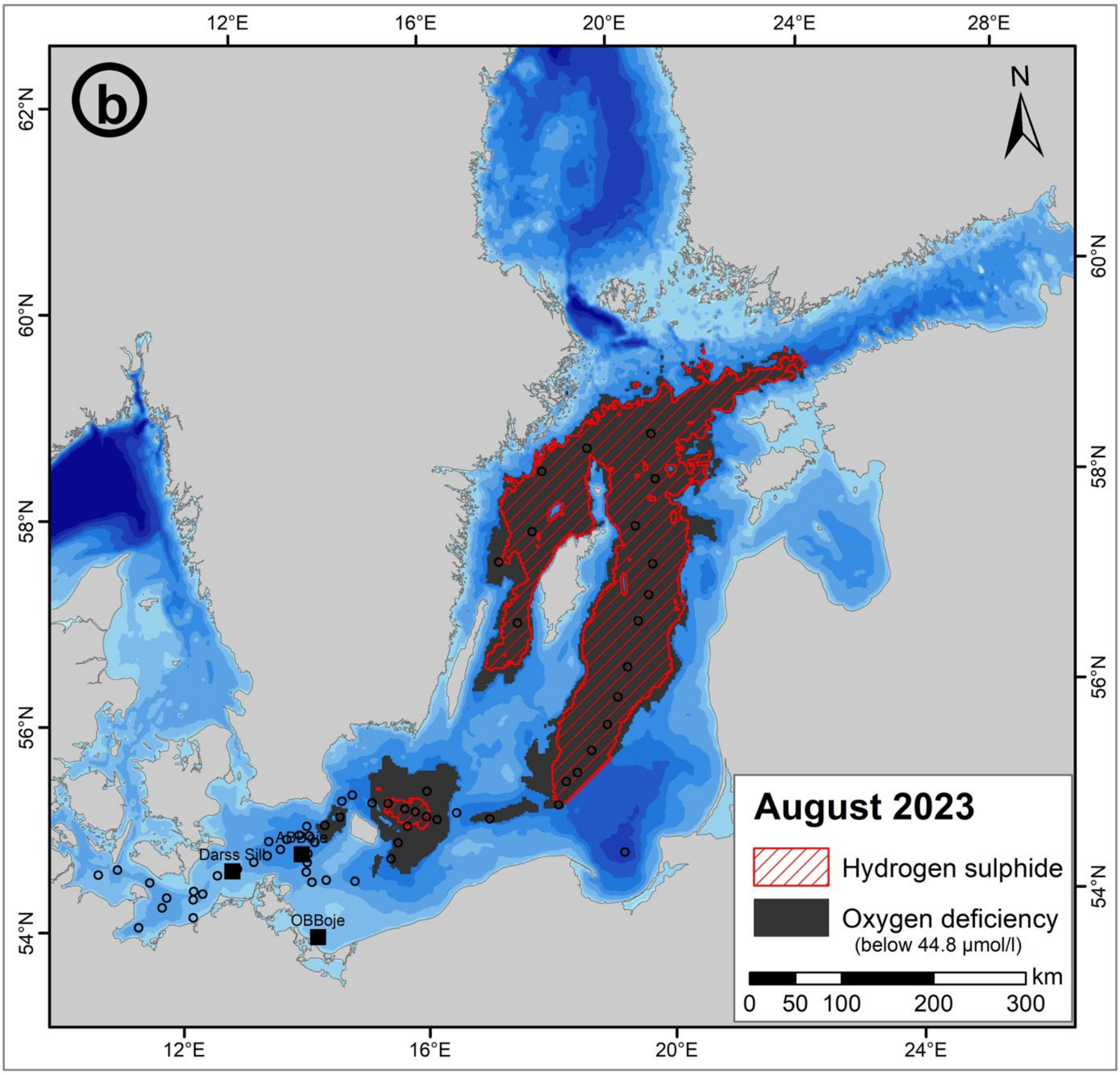


Fig. 1: Location of stations (■ MARNET- stations) and areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea. a) The situation in March 2023. b) The situation in August 2023.

2 General meteorological conditions

The following description of weather conditions in the southern Baltic Sea area is based on an evaluation of data from the Germany's National Meteorological Service (DWD), the Federal Maritime and Hydrographic Agency (BSH), the Swedish Meteorological and Hydrological Institute (SMHI), the Institute of Meteorology and Water Management (IMGW) as well as IOW itself. Table 1 gives a general outline of the year's weather with monthly mean temperature, sunshine duration, precipitation as well as the number of days of frost and ice at Arkona weather station. Solar irradiance at Gdynia weather station is given in addition. The warm and cold sums at Warnemünde weather station, and in comparison with Arkona, are listed in Table 2 and Table 3.

Focussing at Cape Arkona in the north of Rügen island, the meteorological data show positive temperature anomalies up to 3 K (September) during nine months of the year (cf. Table 1). May, November and almost July were on average and the air temperatures in April (-0.5 K) and August (-0.4 K) were below monthly mean temperature values of the climatic reference period (1991-2020). At station Warnemünde a warm sum of 288.7 Kd (cf. Table 2) was registered for the summertime 2023. This value is only slightly above the previous years (281,4 Kd in 2022 and 284.7 Kd in 2021), which is far above the longterm mean of 163.0 Kd. The warm sum of 2023 is on 6th place of warmest summers (1948-2022) and the considered months showed warm sums given in Table 2. The very high warm sum of September (72.1 Kd) depicts a new record in the long-term data series since the year 1948, and is nearly six times higher than the monthly mean of September. Warm temperatures came along with a very high sunshine duration of 251 hours (140 %) during September.

At Gdynia station (Gdansk Bight), an annual sum of 395 452 J cm^{-2} of solar irradiance was recorded. Within a data series covering 68 years back in time (first compiled by FEISTEL et al. 2008, continued to date), this value takes the 12th rank of these longterm data series 1956-2023. It is much lower than the long-term maximum in 1959 with 457 751 J cm^{-2}, but well above the mean value of 376 036 J cm^{-2}. The sunniest month in 2023 was like in previous years 2021 /2022 June (Table 1). With 72 564 J cm^{-2}, it takes the 5th place in the "Top10" of long-term comparison of monthly mean values and is below the peak value of 80 389 J cm^{-2} in July 1994, which represents the absolute maximum of the entire series since 1956. All other months showed solar irradiance monthly mean values compared to those of the last 68 years as follows: January rank 53; February rank 28, March rank 38, April rank 33, Mai rank 4; July rank 41; August rank 55, September rank 4; October rank 49; November rank 15 and December rank 50.

Table 1: Monthly averaged weather data at Arkona station (Rügen Island, 42 m MSL) from DWD (2024). t: air temperature, Δt: air temperature anomaly 1991-2020, s: sunshine duration, r: precipitation, Frost: days with minimum temperature below 0 °C, Ice: days with maximum temperature below 0 °C. Solar: solar irradiance in J cm⁻² at Gdynia station, 54°31' N, 18°33' O, 22 m MSL from IMGW (2024). Percentages are given with respect to the long-term mean (period 1991-2020). Maxima of the year 2023 are shown in bold. November /December of the year 2022 are listed because of the seasonal analysis of the winter half-year.

Month	*t*/°C	Δ*t*/K	*s*/%	*r*/%	Frost/d	Ice/d	Solar/J cm^{-2}
November 2022	7.4	1.4	83	35	3	-	6132
December 2022	2.1	-0.7	122	124	11	4	4055
January	4	2,5	75	140	7	**1**	4876
February	3,0	1,4	128	110	**11**	-	12180
March	4,5	1,2	95	147	8	-	26158
April	6,1	-0,5	105	-	2	-	41547
May	10,8	0,0	123	-	-	-	69858
June	16,8	2,2	127	47	-	-	**72564**
July	17,5	0,1	94	137	-	-	57657
August	17,4	-0,4	72	150	-	-	43954
September	**17,7**	**3,0**	**140**	26	-	-	39043
October	11,7	1,5	82	185	-	-	16139
November	5,9	0,0	79	**213**	6	-	7705
December	3,8	1,0	78	122	7	-	3771

Table 2: Sums of daily mean air temperatures at the weather station Warnemünde (data: DWD 2024b. The 'cold sum' (CS) is the time integral of air temperatures below the line t = 0 °C, in Kd, the 'heat sum' (HS) is the corresponding integral above the line t = 16 °C. For comparison, the corresponding mean values 1948–2022 are given. November /December of the year 2022 are listed because of the seasonal analysis of the winter half-year.

Month	CS 2022/23	Mean	Month	HS 2023	Mean
November 2022	0	2.3 ± 5.9	April	0	0.9 ± 2.3
December 2022	29.3	19.9 ± 27.3	May	2.3	6.1 ± 7.4
January	1.5	36.5 ± 38.9	June	65.1	26.2 ± 18.6
February	0	29.3 ± 36.8	July	69.6	59.6 ± 36.7
March	0	8.0 ± 12.0	August	75.1	56.0 ± 34.5
April	0	0 ± 0.2	September	72.1	12.6 ± 13.1
			October	4.5	0.5 ± 1.5
Σ 2022/2023	**30.8**	**95.9 ± 84.2**	**Σ 2023**	**288.7**	**163.0 ± 76.7**

Table 3: Sums of daily mean air temperatures at the weather station Arkona (data: DWD 2024b). The 'cold sum' (CS) is the time integral of air temperatures below the line t = 0 °C, in Kd, the 'heat sum' (HS) is the corresponding integral above the line t = 16 °C. November /December of the year 2022 are listed because of the seasonal analysis of the winter half-year.

Month	CS 2022/23	Month	HS 2023
November 2022	0	April	0
December 2022	21.8	May	0
January	1.4	June	38.1
February	0.9	July	48.1
March	0.2	August	50.9
April	0	September	53.4
		October	2.5
Σ 2022/2023	**24.3**	**Σ 2023**	**193**

2.1 Ice winter 2022/23

For the southern Baltic Sea area, the Warnemünde station shows a cold sum of 30.8 Kd (Table 2) referring to the air temperature of the winter 2022/2023. After the record winter 2019/2020 (cold sum of 0 Kd) the recent winter season is ranked on 15th place of warm winters in comparative data from 1948 to date. It continues the series of warm winters during the latest years showing low cold sums: 2022/2021 (15.9 Kd), 2020/2021 (32.7 Kd), 2019-2020 (0 Kd) and 2018/2019 (18.3 Kd). Since the year 2012 all values plot below the long-term average of 95.9 Kd. The winter months November 2022, January to April 2023 were much too warm with cold sums of 0 Kd and 1.5 Kd in January. Only December 2022 was with 29.3 Kd, which is above the long-term mean of December with 19.8 Kd. The anomalies of monthly air temperatures showed positive values in general (Table 1). Only December 2022 with -0.7 K and April with -0.5 K were too cold.

In comparison, the cold sum at Arkona station is in the same magnitude of 24.3 Kd (Table 3) and represents as well a warm winter. Recent winter seasons show at Arkona slightly lower values than in Warnemünde (station Arkona: 2021/22 with 11.2 Kd, 2020/21 with 30.2 Kd, 2019/20 with 0 Kd and 2018/2019 with 14.6 Kd. Given the exposed location of the Arkona station at a headland surrounded by water masses at the northernmost coast of Rügen Island, the local air temperature development is under an even stronger influence by the water temperature of the Baltic Sea than at Warnemünde. Thus, winter values at Arkona are frequently higher, while summer values are lower (cf. Table 2 & Table 3).

The winter season recorded 42 days of frost and 5 ice days (daily max below 0 °C) in the time span December 2022 to April 2023 (Table 1). A longer cold spell occurred at the end of the year 2022 from December 8th to 19th. The local ice conditions at the German Baltic Sea coast were generally classified as weak and it was the 11th weak ice winter in a role (ALDENHOFF 2023). Icing occurred only in small areas in sheltered lagoons for a short period in the mid of December (Kleines Haff, Darss-Zings lagoon chain and lagoons of Rügen island). All german offshore areas stayed free of ice during this winter season.

For the whole Baltic Sea area a maximum ice coverage of 81 000 km² was observed at March 8th (Fig. 3). This maximum extent of ice corresponds to some 20 % of the Baltic Sea's area (415 266 km²), and was largely centred in the Bothnian Bay, eastern Gulf of Finland and Estonian sheltered waters between the islands Hiiumaa, Saaremaa and mainland. The observed maximum ice extent is classified as mild in the time series of 303 years (Fig. 2). First icing occurred at mid November in the Bothnian Bay and last ice melted at the end of May (ALDENHOFF 2023).

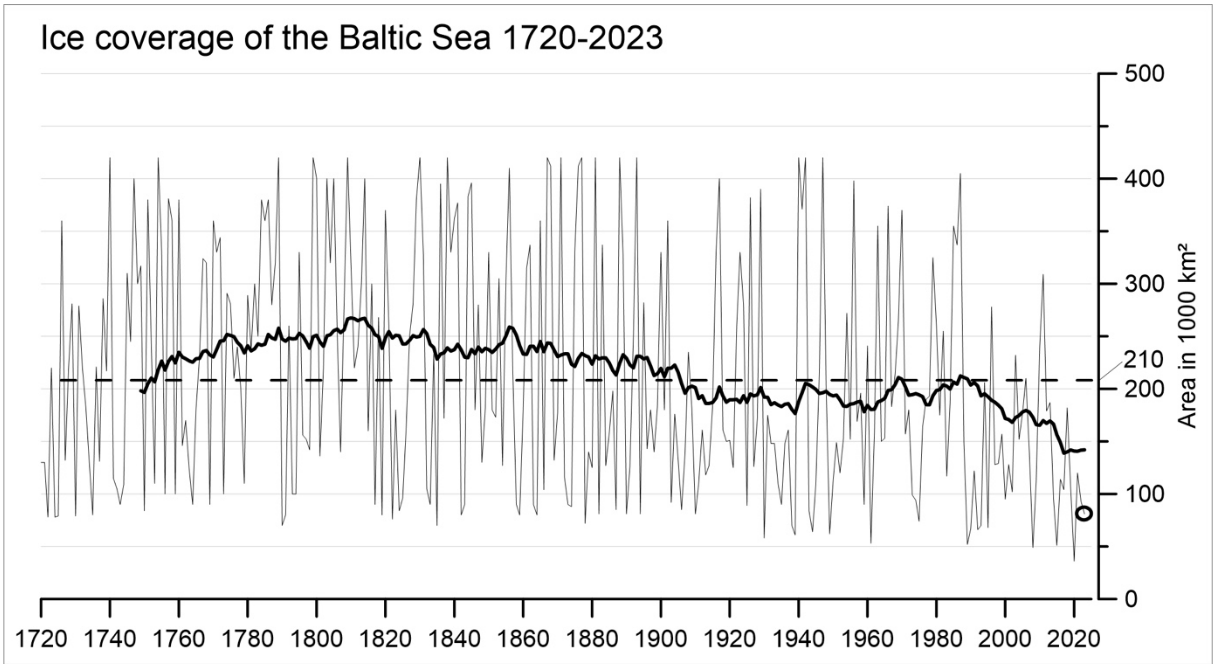


Fig. 2: Maximum ice covered area in 1 000 km² of the Baltic Sea in the years 1720 to 2023 (from data of SCHMELZER et al. 2008, ALDENHOFF 2023). The long-term average of 210 000 km² is shown as dashed line. The bold line is a running mean value over the past 30 years. The ice coverage in the winter 2022/2023 with 81 000 km² is encircled.

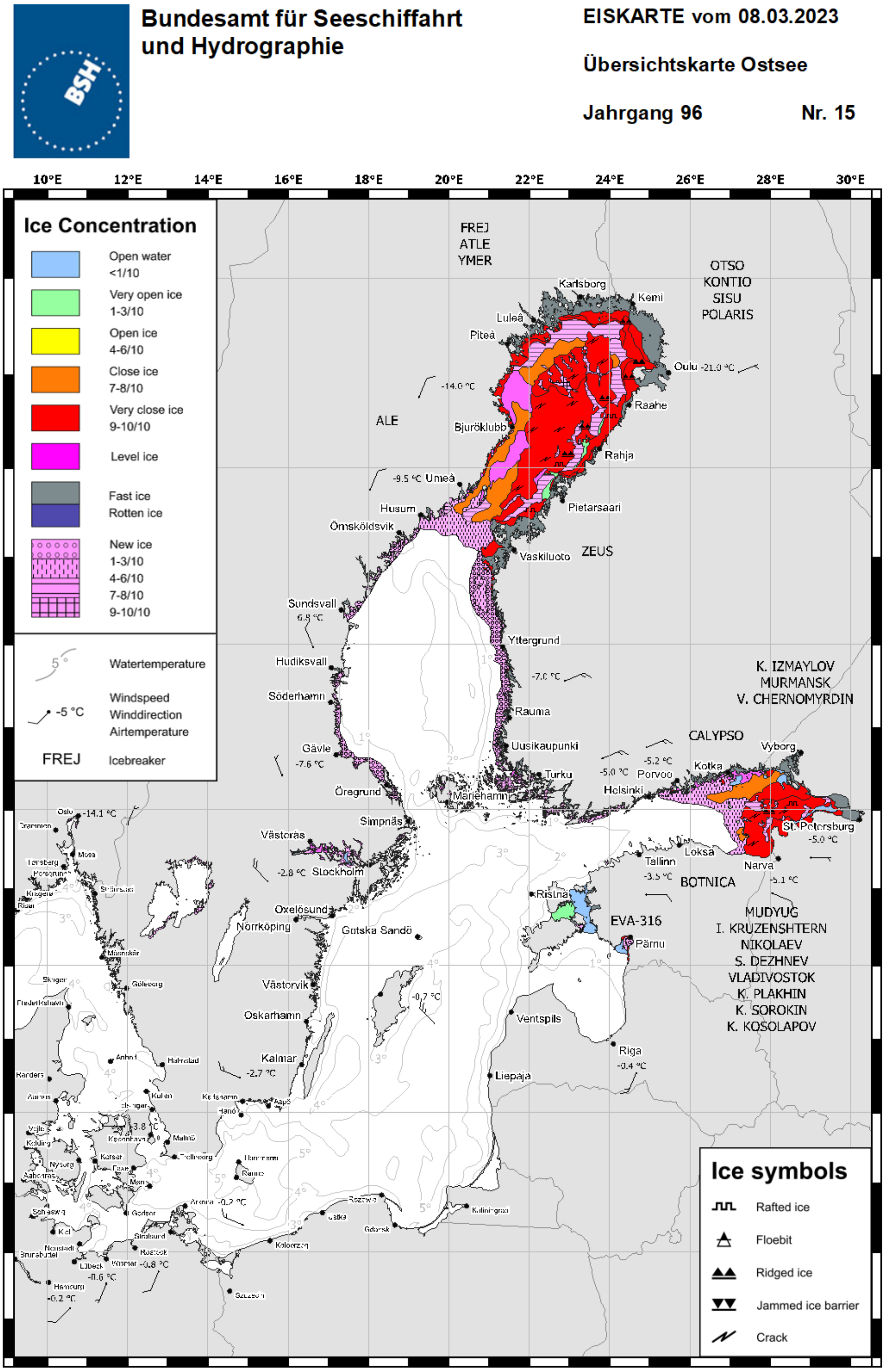


Fig. 3: Maximum ice coverage in the winter 2022/2023 on March 8th – ice concentration in colour code and ice type in symbols (ALDENHOFF 2023).

2.2 Wind conditions

In general, the year 2023 was a more windy one close to the long-term mean compared to the previous series of five light windy years (2018-2022). Fig. 4 to Fig. 5 and Fig. 6b illustrate the wind conditions at station Arkona throughout 2023. The year 2023 of intensified westerly to southwesterly winds (Fig. 5) match with the trend towards prevailing south-west winds that began in 1981 (HAGEN & FEISTEL 2008) and continues today. Comparing the east component of the wind (for westerly winds, i.e. wind directed eastward) with an average of 2.4 m s^{-1} (Fig. 4b) with the climatic mean of 1.9 m s^{-1} (reference period 1991-2020), westerly winds were in 2023 much more dominant than the mean.

According to the wind-rose diagram (Fig. 5), north-western to south-western directed winds account for about 61 % of the annual sum, which is of the same magnitude like 2022 (60 %) and 2020 (61 %), but a bit lower compared to 2021 (67 %). These directions can potentially lead to inflow conditions of saltwater from the North Sea. Easterly to north-easterly winds account for another 22 % in 2023 (20 % in 2022, 18 % in 2021, 24 % in 2020) and can induce outflow conditions.

The annual mean wind speed of 7.29 m s^{-1} (Fig. 4a) is close to the average of 7.35 +/- 0.44 m s^{-1} of the 50 years long time-series at staion Arkona (1973-2023) and the reference period 1991-2020 with a mean of 7.34 m s^{-1}. The maximum wind speed in that period was reached with 8.41 m s^{-1} in 1990 and the minimum value occurred in 2018 – the warmest year on record – with 6.5 m s^{-1} (based on DWD data, 2024b). Since the year 2009 all following years showed an annual mean value below the long-term mean 7.34 m s^{-1}. Eleven high-wind days of over 15 m s^{-1} daily mean are registered during 2023: October 20th (19.9 m s^{-1}, E), August 8th (17,1 m s^{-1}, W), November 23rd (16.8 m s^{-1}, NW), December 22nd (16.5 m s^{-1}, NW), February 20th (16 m s^{-1}, W), April 1st (15.9 m s^{-1}, ENE), to list the top ones . In addition to the daily means, a view at high values of hourly means and maximum gusts enables to detect short, but intensive wind events of violent character. Some storms are regionally restricted to some hours only with no significant impact on the daily mean value. However, they can lead to major damages. Like in the previous two years 2021, 2022 again in 2023 the maximum daily mean, hourly mean and gust were registered all at the same day. At October 20th the maximum daily mean (19.9 m s^{-1}), maximum hourly mean (26.4 m s^{-1}) and the maximum gust of the year (37.0 m s^{-1}, 12 Bft) was registered at station Arkona. This 2023 hourly maximum value of 26.4 m s^{-1} are comparable to previous peak values in the time-series, for example an hourly mean of 30 m s^{-1} in 2000, 26.6 m s^{-1} in 2005; and 25.9 m s^{-1} in December 2013. This October-storm showed an eastern wind direction and caused in addition to a generally elevated sea level (high stand) of around +40 cm MSL (Fig. 6a) a strong storm surge at the coasts of the western Baltic Sea. Fig. 8 shows tide gauge data of several stations along the German coast compared to Landsort and Kronstadt in the central and north-eastern Baltic Sea. At the autonomous MARNET stations Arkona Sea und Darss Sill were wave heights of 6 m and 4 m measured, which are remarkable for this sea region. Intensive damages were registered at the coasts of Rügens island and Schleswig-Holstein. The sea level at Flensburg showed a maximum of +2.27 m MSL, which is the third strongest storm surge after the years 1872 and 1904 in this region (PERLET-MARKUS, 2023). Another storm surge during 2023, but of much lower magnitude, occurred at April 1st with highstands of +1.09 m MSL at Flensburg and +0.75 m MSL at Warnemünde (DÜSTERHÖFT-WRIGGERS & HOLFORT 2023).

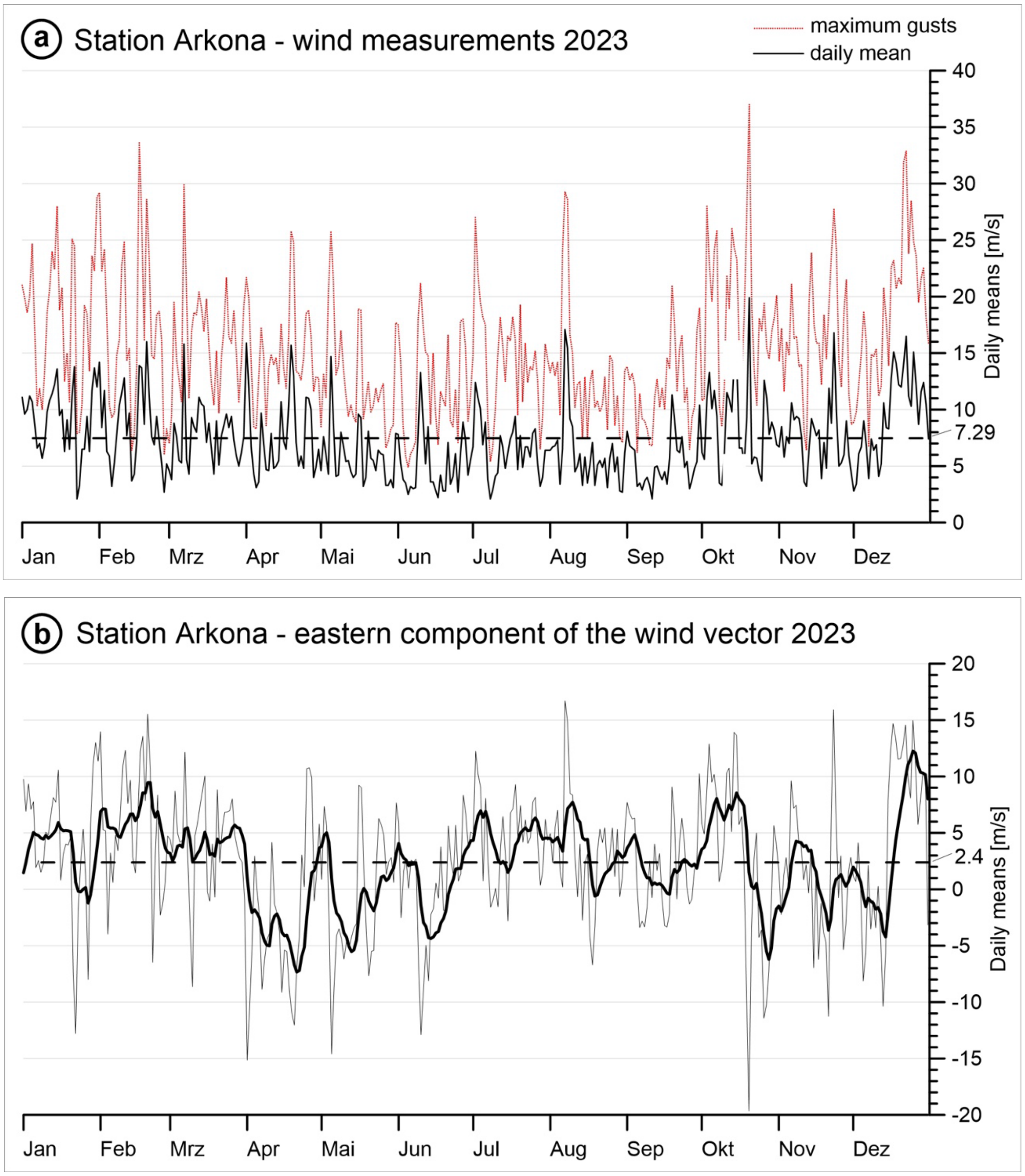


Fig. 4: Wind measurements at the weather station Arkona (from data of DWD 2024a). a) Daily means and maximum gusts of wind speed, in **m s**$^{-1}$*, the dashed black line depicts the annual average of 7.29* **m s**$^{-1}$*. b) Daily means of the eastern component (westerly wind positive), the dashed line depicts the annual average of 2.4* **m s**$^{-1}$*. The line in bold is filtered with a 10-days exponential memory.*

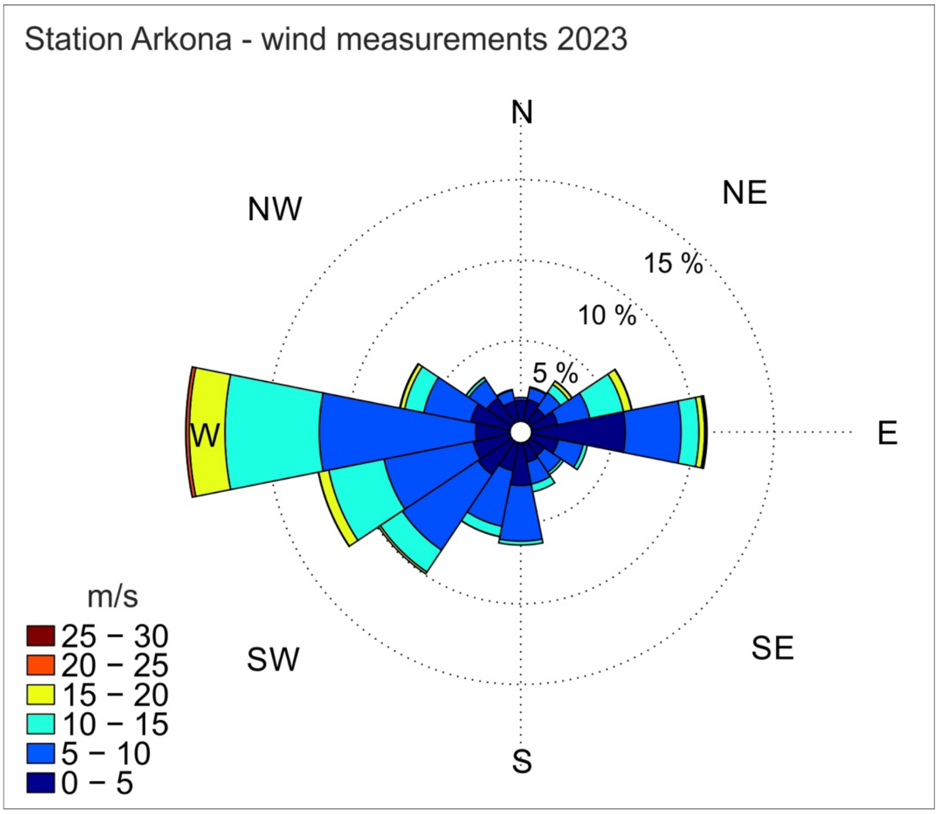


Fig. 5: Wind measurements at the weather station Arkona (from data of DWD 2024a) as windrose plot. Distribution of wind direction and strength based on hourly means of the year 2023.

3 Water exchange through the straits

3.1 Water level at Landsort

The Swedish tide gauge station at Landsort Norra, south of Stockholm, provides a good description of the mean water level in the Baltic Sea (Fig. 6a), as it is more or less unaffected by windshift and located in the centre of the large scale seiche of the Baltic Basin (LISITZIN 1974, JACOBSEN 1980, FEISTEL et al. 2008).

In the course of 2023, the series of years (2017-2022) showing weak inflow activity into Baltic Sea was interrupted. Around Christmas a total volume of 222 km³ was imported, which raised the sea level at station Landsort Norra from -17.1 cm MSL to 44.6 cm MSL (December 15th – 25th). In addition, several small less continuous inflow pulses occurred during 2023. Three of them happened in a role in January from 1st to 5th (12.9-34.4 cm MSL), January 7th to 15th (7.7-38.9 cm MSL) and January 25th to February 1st (-1.3-32.0 cm MSL) and showed total inflow volumes of 77 km³, 108 km³ and 119 km³. The next pulse occurred in the end of April from 22nd to May 3rd 2023 of 124 km³ (-33.5 cm MSL to 3.1 cm MSL). In summertime from June 13th to July 4th (-25.2-26.1 cm MSL) and July 16th to August 7th (-1.9-42.6 cm MSL) volumes of 169 km³ and 142 km³ were pushed into the western Baltic. During October occurred two pulses in a role from September 30th to October 7th (4.7-40.6 cm MSL) and October 12th to 13th (8.9-43.3 cm MSL) with volumes of 126 km³ and 127 km³. These total volumes of inflow water are calculated after NAUSCH et al. 2002, FEISTEL et al. 2008. The December 2023 inflow represent a “classic” situation of continuous and rapid sea level changes of more than 50 cm, which indicate major events. This December inflow imported a salt mass of 1.7 Gt into the Baltic Sea (Fig. 7) and was classified as midsize Major Baltic Inflow (MBI) after the calculation method of MOHRHOLZ (2018). It was the first MBI event after February 2016 and for comparison, the large Major Baltic Inflow of December 2014 showed a rapid continuous sea level rise from -47 cm MSL to +48 cm MSL within 22 days and 3.98 Gt of imported salt mass (MOHRHOLZ et al. 2015). Rapid rises of the sea level like this ones are usually only caused by an inflow of North Sea water through the Sound and Belts. They are of special interest for the ecological conditions of the deep-water in the Baltic Sea. Such events are produced by storms from westerly to north-westerly directions, as the correlation between the sea level at Landsort Norra and the filtered wind curves illustrates (Fig. 6b). Only in mid December to Christmas time a longer intensified phase (weeks) of a positive southeastern wind component (northwesterly wind) occurred during 2023, which caused this rapid rise of 61.7 cm at Landsort Norra. Other wind events of this direction were early interrupted (Fig. 6b), hampered a steady inflow and showed only a stepwise sea level rise (for example mid to end of June).

In general, the sea level fluctuations in the course of the year 2023 registered a high stand of +50.4 cm MSL at August 8th (Fig. 6a, hourly means), but other high stands of nearly the same level occurred in mid October and end of December. The lowest water level of 2023 was reached at April 20th with -36.6 cm MSL after a longer period of easterly winds since the end of March (Fig. 6a,b) and prepared the weak inflow pulse end of April to May.

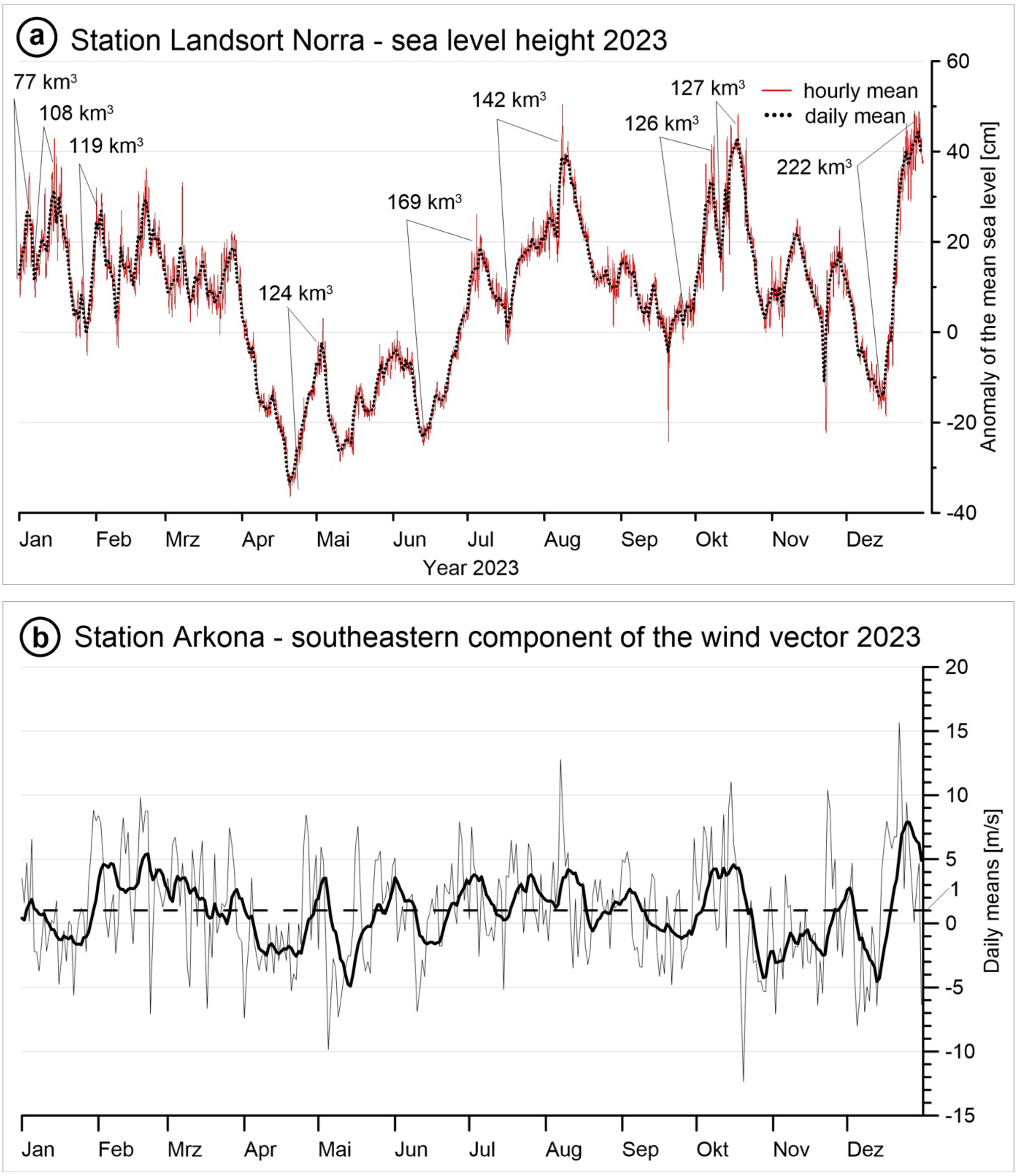


Fig. 6: above (a): Sea level at Landsort as a measure of the Baltic Sea fill factor (from data of SMHI 2024a). below (b): Strength of the southeastern component of the wind vector (northwesterly wind positive) at the weather station Arkona (from data of DWD 2024a). The bold curve appeared by filtering with an exponential 10-days memory and the dashed line depicts the annual average of 1.0 ***m s***$^{-1}$.

Like mentioned, beside rapid sea level rise another measure which leads to the classification of inflow events is the salt mass import (Fig. 7), where the overflow volumes of saline water above 17 PSU are taken into account in more detail. MOHRHOLZ (2018) reviewed all sources of hydrographic long-term data for the historic events and set up a new calculation method in comparison to the criteria of MATTHÄUS & FRANCK (1992). The classic criterion for a Major Baltic Inflow is an import of at least 1 Gt salt mass. Fig. 7 shows the import of salt into the western Baltic Sea for the time span 2019 to 2023 (calculated after MOHRHOLZ 2018). The low, short but rapid rise of three smaller events during January imported a salt mass of 0.75 Gt than the small inflow pulse in the end of April (0.26 Gt). In the end of June another 0.42 Gt and during July-August a stepwise sea level rise imported 0.76 Gt of salt mass. Two inflow pulses during October account to 0.63 Gt. The MBI of December 2023 (1.7 Gt) is clearly ahead of all weak pulses during the last five years.

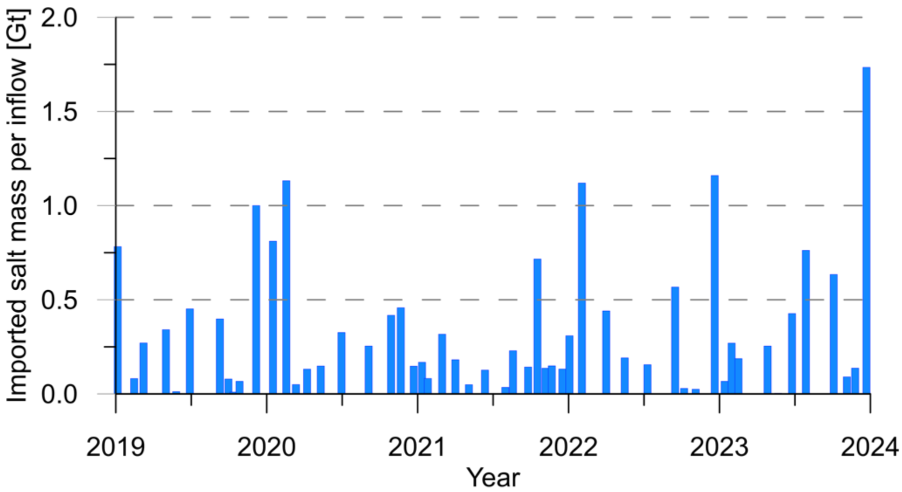


Fig. 7: Salt import by barotrope saltwater inflows into the Baltic Sea during 2019-2023 (calculated after MOHRHOLZ 2018).

3.2 Observations at the MARNET monitoring platform "Darss Sill"

3.2.1 Statistical Evaluation

The determination of bulk parameters that influence the water mass properties at Darss Sill was achieved through statistical analysis of temperature and salinity data collected at various depths. To address short gaps in the time series data for temperature and salinity, a combination of neural network algorithms and numerical modeling was employed (SIM et al., 2022). This approach ensured that the annual statistical analysis remained unbiased.

Shifting focus to a broader perspective, the year 2023 has been officially designated as the warmest year on record. According to the EU's Copernicus Climate Change Service (COPERNICUS 2023), global temperatures approached the critical 1.5 °C threshold, surpassing the previously warmest year, 2016, by a significant margin. In Europe, 2023 was recorded as the second warmest year, with temperatures averaging 1.02 °C above the baseline period of 1991-2020. Throughout 2023, Europe experienced above-average temperatures for 11 months, with September marking the warmest September ever recorded.

Mirroring the global trend of rising temperatures, the Darss Sill surface waters in 2023 also exhibited temperatures significantly higher than the long-term average. The average surface water temperature for 2023 was measured at 10.20 °C, lower than the temperatures in 2020 (10.75 °C) and 2018 (10.54 °C). Despite this, the annual mean surface-layer temperatures for 2023 rank among the top ten warmest since 1992, placing them in the upper quartile. The standard deviation highlighted variability in the surface-layer temperature averages, with the well above average recorded minimum winter temperature being 3.51 °C, aligning closely with the highest values observed historically (4.74 °C, 2020).

This trend is illustrated in Fig. 10, which shows the temperature anomaly of near-surface waters. The analysis uses a climatological baseline from REYNOLDS et al. (2007), covering the years 1982 to 2011. This baseline is closely aligned with the national reference period from 1981 to 2010. The winter and autumn water temperatures were as much as 1.5 K above the long-term average. Summer temperatures, however, remained close to the long-term average, with occasional deviations due to cold anomalies in June and August, likely caused by episodic upwelling events.

Salinity measurements and their standard deviations at the Darss Sill station are recorded at different depths: 7 meters – 9.68±1.63 g kg^{-1}, 17 meters – 12.24±2.62 g kg^{-1}, and 19 meters – 13.36±3.56 g kg^{-1}. The readings from the deeper sensors capture near-bottom salinity variability, thus serving as sensitive indicators of inflow activity. Unlike in 2016 (15.56 ± 3.45 g kg^{-1}) and 2014 (14.91 ± 3.40 g kg^{-1}), which both experienced strong inflow events, the year 2023 still exhibited above-average mean salinity and increased variability at the near-bottom, suggesting moderate inflow activity in 2023. The variability at the 19-meter depth was notably high.

Finally, we evaluated the minimum and maximum temperatures at a 7-meter depth at Darss Sill, revealing that 2023 had the second warmest winter since 1995. The lowest temperature, recorded on February 2nd was 3.51 °C. As illustrated in Fig. 10, the entire winter was nearly 2 °C warmer than usual. The highest temperature, recorded on July 25th, was 19.96 °C, making it the sixth highest on record. The temperature range in 2023 was close to the long-term mean, influenced by the warmer conditions in winter and autumn.

3.2.2 A storm surge in October

The Baltic Sea experienced its most severe storm surge since 1872 (FEUCHTER et al. 2013) on the night of October 20 to 21, 2023. A low-pressure system, named Wolfgang by the German Weather Service, originated off the west coast of Spain and traveled across the Bay of Biscay to Great Britain and Ireland, where it was designated as Storm Babet by the Met Office. It then moved towards Scandinavia, encountering a blocking high-pressure area named Wiebke. This interaction led to higher horizontal pressure gradients and generated strong easterly winds over the Baltic Sea, driven by the cyclonic rotation of the low-pressure system and the anticyclonic rotation of the high-pressure area. The highest water level recorded was 2.27 meters above mean sea level at Flensburg, causing approximately 200 million euros in damage to coastal and maritime structures in Germany.

Fig. 8 illustrates the temporal evolution of water levels at various stations, sorted from west to east, primarily in the western Baltic Sea. Notably, the Flensburg gauge ceased functioning at levels above 2.00 m, but a temporarily installed gauge recorded the peak of 2.27 m. In contrast, the water level estimates at Landsort showed no signs of the high levels observed in the western Baltic Sea. However, at Kronstadt, a decrease in water levels was noted, aligning with expectations. A similar phenomenon occurred in the German Bight, where the low-pressure system led to exceptionally low water levels.

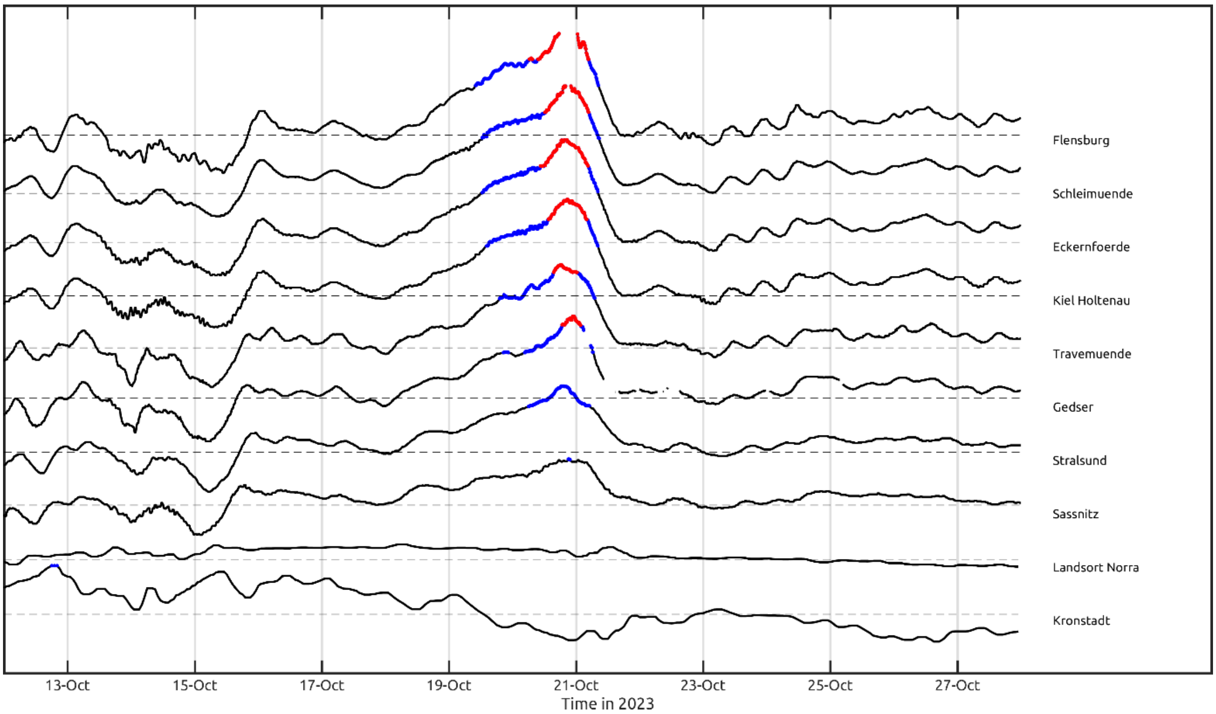


Fig. 8: Temporal development of water levels a several gauges in the Baltic Sea. For visualisation purposes, the water levels a shift by an offset. The blue lines indicate water levels above 1 m, and the red lines mark water levels 1,5 m above normal.

3.2.3 Temporal development at Darss Sill

The year 2023 began in the aftermath of a marine heat wave that started at the end of October, resulting in water temperatures being 2 K higher than usual. Despite these high temperatures, thermal stratification was low. According to the stratification index G by (MATTHÄUS & FRANCK 1992) shown in the lower panel of Fig. 9 values intermittently exceeded 0.2, yet salinity remained mostly uniform throughout the water column.

By the end of March, the wind shifted to easterly directions and subsided, prompting some initial inflow activity. The eastward component of currents at Darss Sill indicated positive values, signalling the inflow of saline water into the Baltic Sea, as depicted in Fig. 12. However, salinity levels between the bottom and surface were nearly identical, leading to the transport of only brackish surface water into the Baltic Sea. At the end of May, stratification shortly increased and some saline water entered the Baltic Sea.

Salinity and stratification remained low through May, interrupted only by minor spillover inflows. In May, average wind speeds gradually decreased from 8 m s^{-1} to 2 m s^{-1} in June. This reduction in wind mixing facilitated the development of thermal stratification, which was accompanied by increased salinity stratification. The resulting two-layer flow caused a separation of well-oxygenated surface waters from the stagnant bottom waters (Fig. 11), leading to a decline in oxygen saturation. Despite these changes, the vector diagram (Fig. 12) did not show significant inflow activity, except the some minor inflow activity at the end of April.

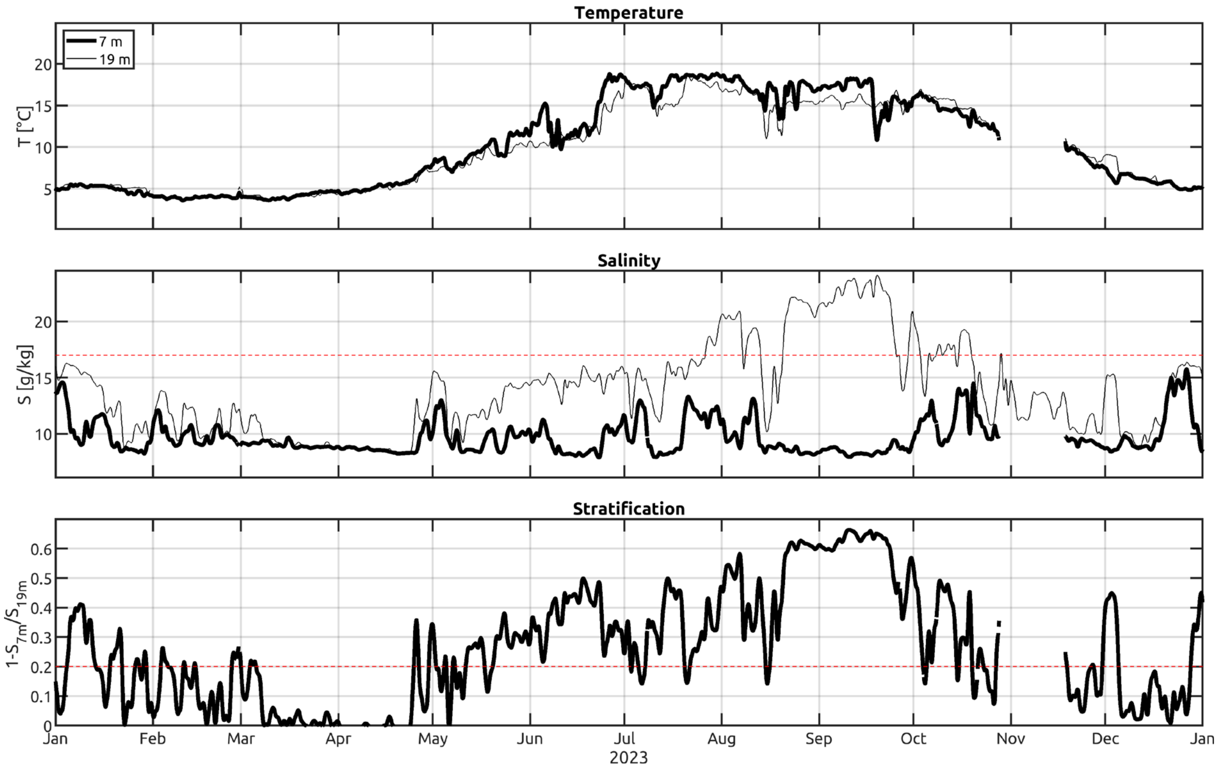


Fig. 9: Water temperature (upper panel) and salinity (middle panel) measured in the surface layer and the near bottom layer at Darss Sill in 2023. The red dashed line indicates the salinity threshold of 17 g/kg. In the lower panel we show a stratification measure G according to (MATTHÄUS & FRANCK 1992). Here the red dashed line marks the stratification threshold of 0.2.

In the first week of June, wind speeds intensified, reaching peak values of 14 m s^{-1} at Darss Sill from northeasterly directions for the next five days. This increased wind mixing disrupted the salinity stratification. Given that easterly winds favour upwelling at Darss Sill, a cold water tongue reached the station, causing a temperature drop of 5 K in the surface mixed layer, which is also marked by an upwelling signature in Fig. 10. Although the upwelling did not appear in surface oxygen saturation, likely obscured by a bloom, its impact was evident in the bottom oxygen saturation. The upwelling brought stagnant, low-oxygen water from the Arkona Basin to Darss Sill, causing oxygen saturation to fall to 60%. Oxygen levels rebounded nearly to surface values by mid-July as the upwelling subsided.

In early August, wind speeds again increased, reaching a peak of 18 m s^{-1} from southwesterly directions. The salinity difference of 7 g kg^{-1} and the low oxygen saturation of 60% in the bottom waters were mixed away, resulting in a homogenous water column in terms of salinity, temperature, and oxygen.

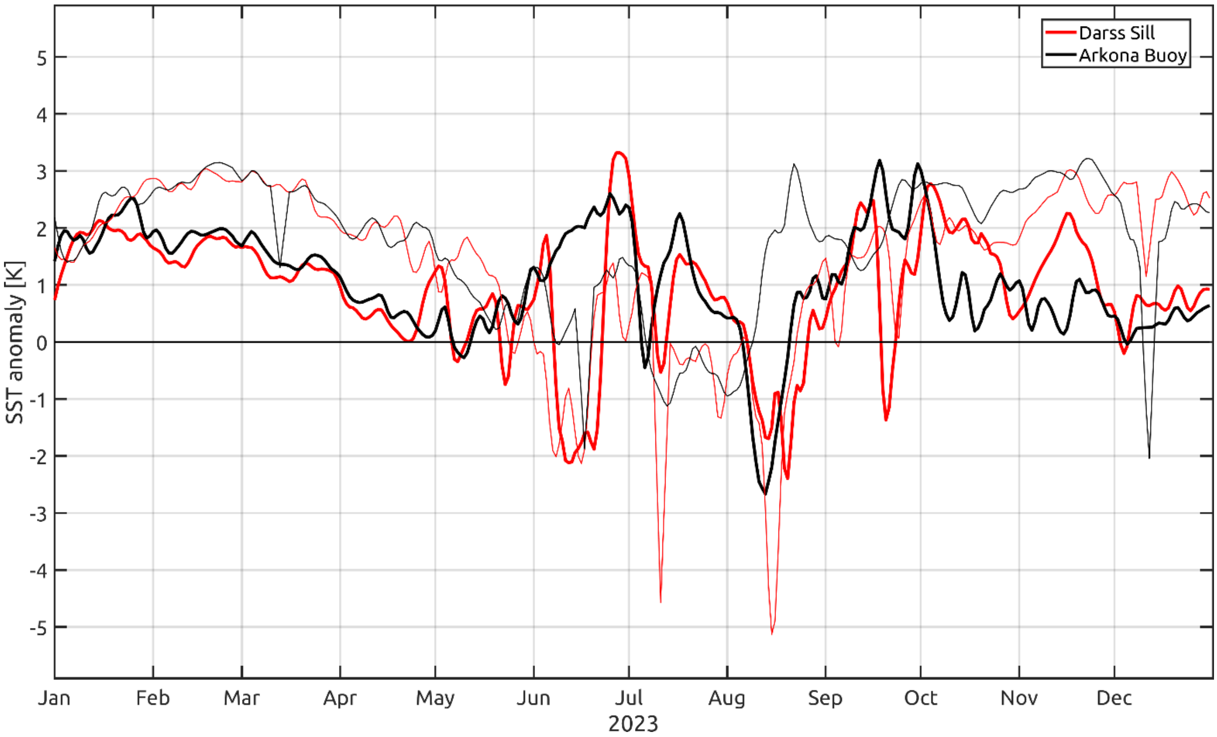


Fig. 10: Deviation of near surface temperature from the climatology at Darss Sill and Arkona Buoy in 2023. The climatology was built for the national reference period 1982-2011 and is based on the dataset of REYNOLDS *et al., 2007. The thin lines show the anomaly from 2020.*

Following a period of calm, the next month was characterized by low wind speeds of 2-3 m s^{-1} from southerly directions. This reduced mixing led to pronounced saline stratification, with bottom salinity levels reaching 18-20 g kg^{-1}, while surface salinity remained at 8 g kg^{-1}. The strong stratification, coupled with high bottom salinity, suggested a baroclinic inflow, corroborated by the vector diagram (Fig. 12). From the beginning of September, the eastward velocity component of the bottom current showed positive values.

The onset of the first autumn storm at the end of October ceased the baroclinic inflow activity and homogenized the water column.

In December, wind patterns in the Baltic Sea conformed to the typical behavior of a barotropic inflow. For the first ten days of the month, winds blew from an easterly direction, effectively lowering the overall water level in the sea. On December 12th, the wind direction shifted to the southwest and intensified, reaching peak speeds of 20 m s^{-1} during Storm ZOLTAN, which affected northern Germany from December 21st to 22nd.

This shift in wind direction caused the water level at the Landsort gauge to rise by approximately +60 cm, triggering a barotropic inflow into the Baltic Sea. The total volume of this inflow was estimated at around 200 million cubic meters, resulting in an increase in bottom salinity levels to 17 g kg^{-1}. The currents at Darss Sill showed a strong eastward component for 14 days during this period. An initial estimate suggests that approximately 1.7 Gt of salt were transported into the Baltic Sea.

By the last week of December, the decrease in wind speed could not sustain the water level, and the inflow ceased.

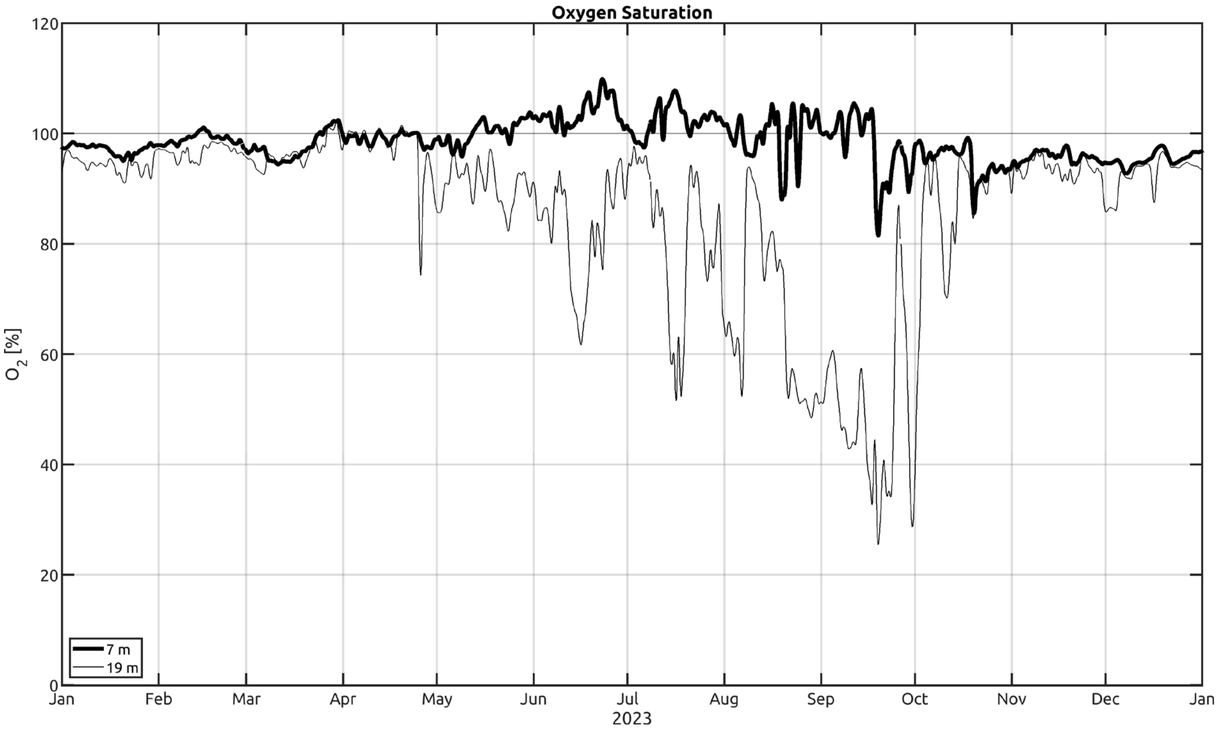


Fig. 11: Oxygen saturation measured in the surface and bottom layer at the Darss Sill in 2023.

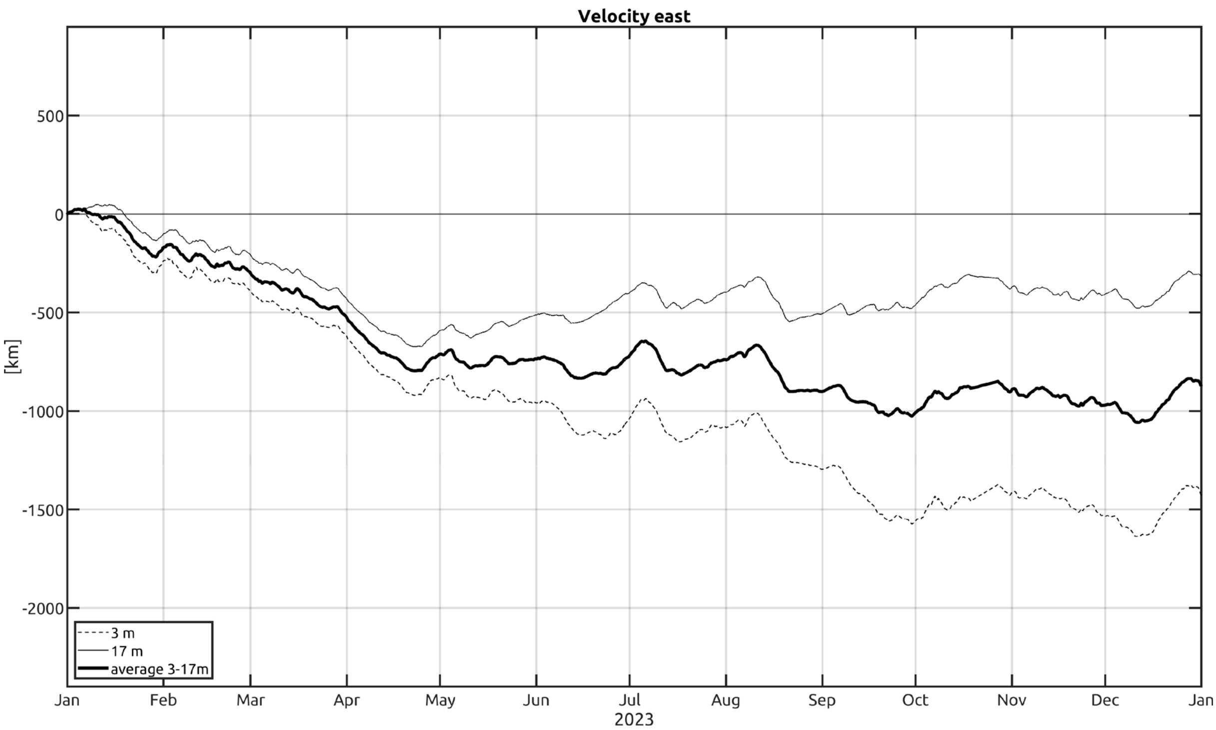


Fig. 12: East component of the progressive vector diagrams of the current in 3 m depth (solid line), the vertical averaged current (thick line) and the current in 17 m depth (dashed line) at the Darss Sill in 2023.

3.3 Observations at the MARNET monitoring buoy "Arkona Basin"

3.3.1 Temporal development until summer

The Arkona Basin monitoring station (AB), which is featured in this chapter, is strategically located about 20 nautical miles northeast of Arkona, at a water depth of 46 meters. In 2023, the station maintained a complete record of measurements. The optode-based oxygen measurements at this station were calibrated using the Winkler method. This calibration process relied on water samples that were collected and analyzed during the regular maintenance cruises conducted by MARNET. Fig. 13 presents a time series of water temperature and salinity measured at depths of 7 m and 40 m, representing the conditions of the surface and bottom layers, respectively. Fig. 14 follows with the corresponding oxygen concentrations, displayed as saturation values in a manner consistent with the previous chapter.

Similar to observations at Darss Sill, the Arkona Basin station AB also experienced an anomalously warm surface layer during the first three months of the year, as illustrated in Fig. 10. The coldest daily mean temperature recorded at station AB was about 3.93 °C on March 11th, shown in Fig. 13. This temperature was approximately 0.5 K higher than the minimum temperatures measured at Darss Sill a month earlier. The temperature dynamics at the Arkona Basin are primarily influenced by local atmospheric fluxes, while those at Darss Sill are more significantly impacted by lateral advection. This difference in influencing factors likely explains the variations observed between the two locations.

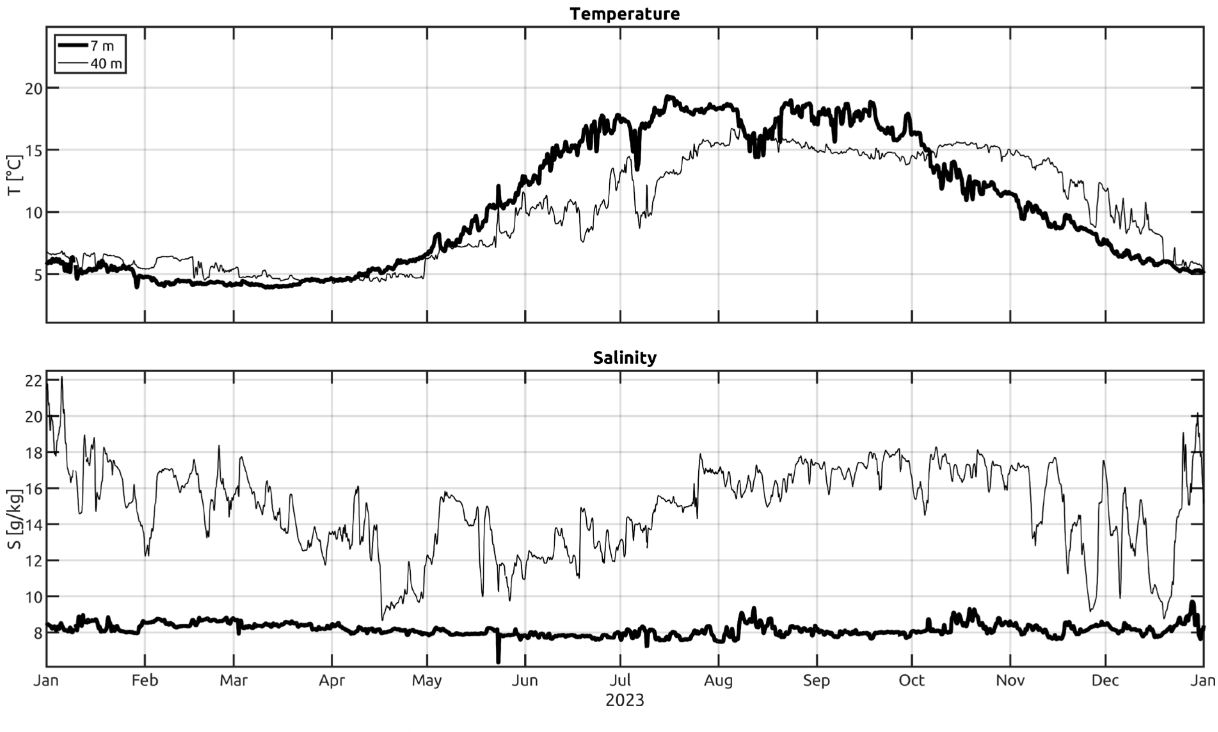


Fig. 13: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station AB in the Arkona Basin in 2023.

In the first two weeks of 2023, the bottom water properties in the Arkona Basin were still heavily influenced by the baroclinic inflow event from late December 2022. Peak salinities in the bottom layers reached 22 g kg^{-1}, suggesting that these water masses originated from Drogden Sill, as maximum salinities at Darss Sill were only 19 g kg^{-1} in December 2022. Declining, but fluctuating salinity levels, marked by occasional spikes, indicate the draining of this bottom pool through the Bornholm Channel (Fig. 13) and some replenishment from Drogden Sill.

Despite the cold water temperatures, which typically reduce respiration rates, the oxygen concentrations in these waters were lower than usual for this period, not dropping below 80 % of the saturation level (Fig. 14). This is attributed to the baroclinic nature of the inflow, which brought in water masses already low in oxygen.

By the end of April, the bottom salinity was still decreasing to a minimum of 9 g kg^{-1} in mid-April. In early May, a new influx of water reached the monitoring station, characterized by salinity levels around 16 g kg^{-1} and higher oxygen content (Fig. 14). Since there were no elevated salinities recorded at Darss Sill during this period, these water masses likely originated from Drogden Sill, confirmed by current data indicating a barotropic inflow (Fig. 12) However, this inflow was too brief to result in significant salinity transport over Darss Sill, further supporting the hypothesis of its Drogden Sill origin.

In June, increased surface heat flux led to pronounced thermal stratification, culminating in a 7 K temperature difference between the surface and bottom layers by the end of the month. The warming trend was briefly interrupted by an upwelling event in early July, coinciding with a severe drop in oxygen saturation to below 50%.

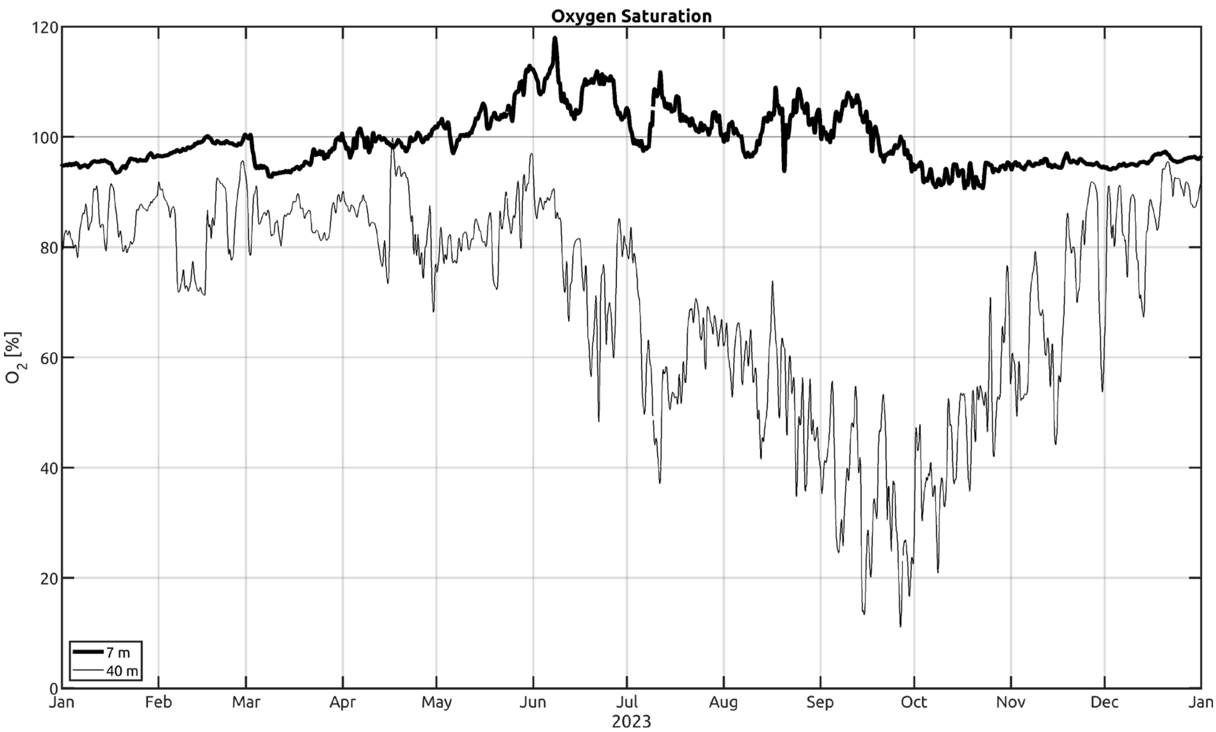


Fig. 14: Oxygen saturation measured in the surface and bottom layer at the station AB in the Arkona Basin in 2023.

Towards the end of July, a weak baroclinic inflow at Darss Sill began to replenish the salt pool in the Arkona Basin, also raising the bottom water temperature to 15 °C. By mid-August, a second baroclinic inflow had established a quasi-steady state of 17 g kg^{-1} in bottom salinity—slightly lower than the 19 g kg^{-1} observed at Darss Sill (Fig. 9). This difference is likely due to mixing during its transit from Darss Sill to the Arkona Buoy and the fact that sensors are placed 5 m above the sea floor, potentially underestimating peak salinities. Concurrently, oxygen levels continued to deteriorate, approaching near-anoxic conditions by early October.

Unfortunately, due to missing oxygen data from October onward, the expected recovery of oxygen levels with the arrival of late-season storms cannot be analyzed (see Section 3.2). However, from October, there was a noticeable decline in bottom salinity and temperature, attributed to the dilution of the bottom pool into the Bornholm Basin and atmospheric cooling coupled with increased wind-induced surface mixing, which eroded the thermocline.

In the third week of December, the water column, previously nearly well-mixed, became stratified again due to a barotropic inflow, causing bottom salinity to rise sharply to peak values of 20 g kg^{-1}.

3.3.2 An upwelling event

Upwelling is a common phenomenon in the Baltic Sea, consistently resulting in notable horizontal temperature gradients (LEHMANN ET AL., 2012; SUURSAAR, 2020). We previously noted the upwelling at Darss Sill in June, which led to a 5-6 K drop in sea surface temperature (SST), as depicted in Fig. 9. In July, the Arkona Buoy also recorded a temperature decrease of 6 K (Fig. 13), although it was only peripherally affected by a cold water filament. Here, we aim to provide a spatial overview of the upwelling event at the start of July.

On July 3rd, the wind strength increased from 5 m s^{-1} to 15 m s^{-1}, originating from a southwesterly direction. This change initiated a basin-wide upwelling, as illustrated in Fig. 15. Significant reductions in SST were observed across multiple regions: the Arkona Basin, the eastern coasts of Öland and Gotland, the northern part of the Gulf of Riga, and the northern coast of the Gulf of Finland all experienced drops in SST of more than 9 K. Notably, at Gotland and in the Gulf of Riga, SST plummeted from 18 °C to below 8 °C within just two days.

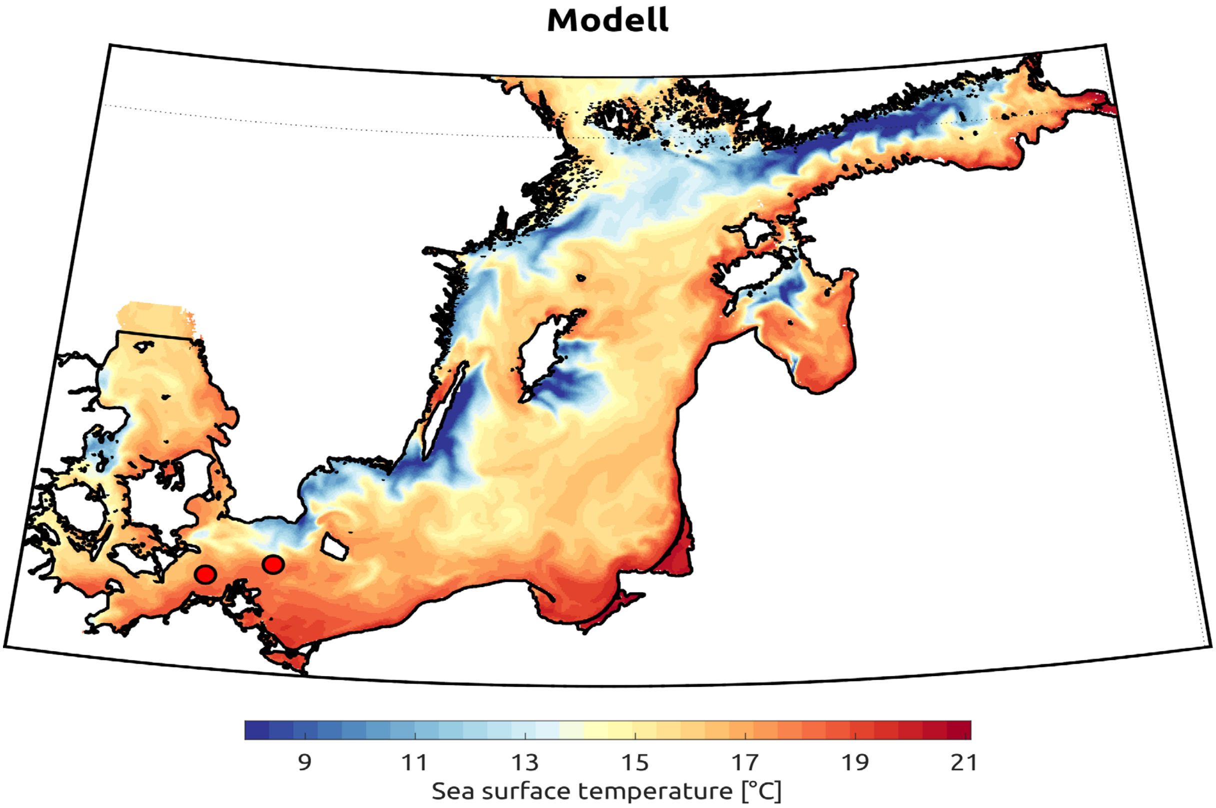


Fig. 15: Modelled snapshot of SST at 6th of July. Due to high cloud coverage, the provide the modelled SST, rather than a satellite snapshot. The two red dots indicate the stations Darss Sill and Arkona Buoy.

3.4 Observations at the MARNET monitoring buoy “Oder Bank”

The water mass distribution and circulation in the Pomeranian Bight are largely influenced by the dynamics between wind patterns, upwelling, and the inflow from the Oder river plume. When westerly winds prevail, the waters in the Pomeranian Bight are well-mixed, with a slight admixture of surface water from the Arkona Basin. Conversely, easterly winds encourage the flow of water from the Oder Lagoon via the Świna and Peenestrom rivers into the Pomeranian Bight, where it stratifies above the bay water off the coast of Usedom. These conditions significantly affect primary production and the vertical oxygen structure in the region.

The Oder Bank monitoring station (OB), situated about 5 nautical miles northeast of Koserow/Usedom at a depth of 15 meters, tracks temperature, salinity, and oxygen at depths of 3 m and 12 m. The oxygen data are validated using water samples analyzed with the Winkler method during regular maintenance cruises. The station operated continuously throughout 2023.

Temperature and salinity measurements from OB are shown in Fig. 16, with corresponding oxygen levels depicted in Fig. 17. As observed at other MARNET stations, the peak summer temperature at OB reached 21.21 °C on June 26th. Surface temperatures at this station are typically higher than those at deeper, more dynamic locations such as the Arkona Basin and Darss Sill (refer to Fig. 9 and Fig. 13). This pattern is a result of the shallower and more protected nature of OB's location. Moreover, the transport of lighter, less saline waters from the Oder

Lagoon overlays the denser, saltier bottom waters, reducing vertical mixing and thus contributing to the warmer surface temperatures observed during average years.

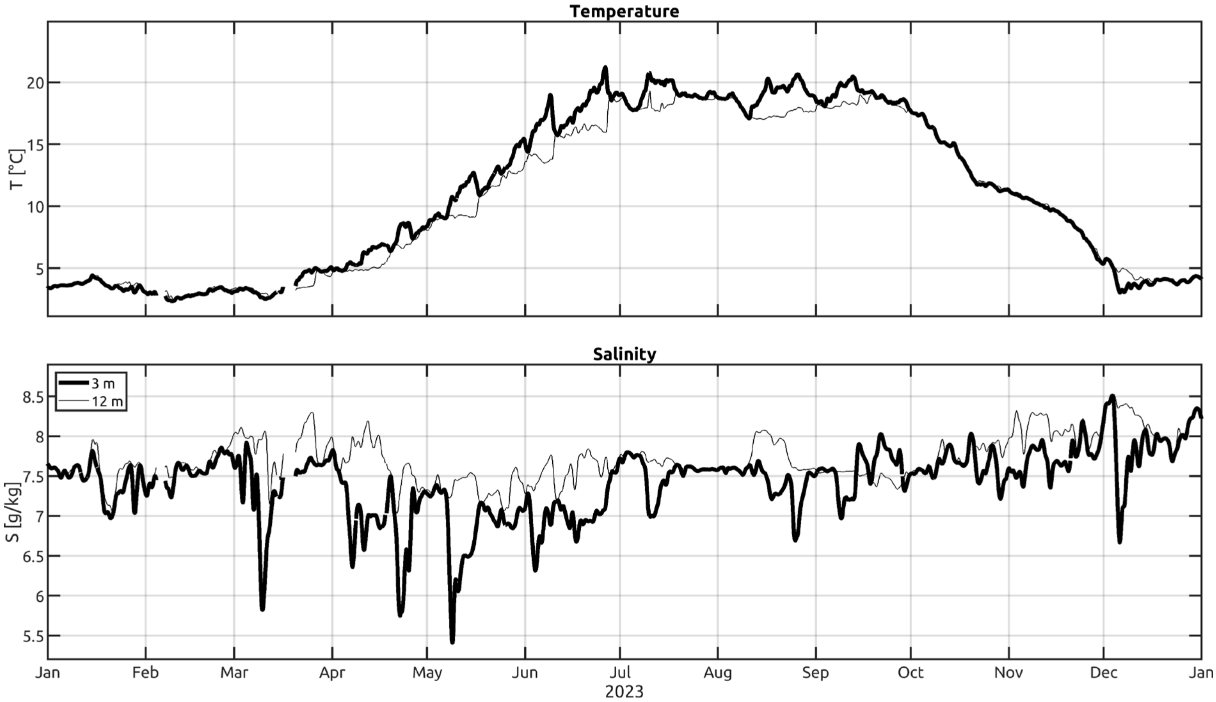


Fig. 16: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station OB in the Pomeranian Bight in 2023.

In mid-March, temperature and haline stratification began to develop in the Pomeranian Bight, with temperature gradients between the surface and bottom layers averaging around 2 K and salinity differences peaking at 0.6 g kg^{-1}. By May, salinity differences reached peak levels of 2 g kg^{-1}.

From an ecological standpoint, one of the most significant consequences of this stratification and the resultant suppression of turbulent mixing was the reduction in near-bottom oxygen concentrations, effectively decoupling the bottom layer from direct atmospheric ventilation. This impact on the oxygen budget of the Pomeranian Bight is evident from Fig. 17, which shows oxygen concentrations at depths of 3 m and 12 m. At the end of March, an early phytoplankton bloom occurred, one month earlier than in 2022, leading to an oxygen oversaturation of approximately 10%. A second bloom in June pushed the near-surface oxygen concentrations to about 20% above the saturation level. Additionally, the influx of nutrient-rich waters from the lagoon likely contributed to locally enhanced production rates, explaining the increased oxygen concentrations in the surface layer. The correlation between increased oxygen in the surface layer and decreased oxygen in the near-bottom layer suggests higher oxygen consumption rates induced by the decomposition of freshly deposited biomass.

The lowest near-bottom oxygen concentrations in 2023 were observed at the end of June, with hourly saturation values dropping to as low as 40%. However, this decrease was an episodic event, likely triggered by an upwelling of bottom waters from the Bornholm Basin or from the deeper channel east of Rügen. This event also led to a collapse of both thermal and saline stratification.

As wind speeds decreased in August, and baroclinic inflow commenced, the waters in the Pomeranian Bight restratified, creating a thermal stratification with a temperature difference of 3 K across the water column. However, for the remainder of the year, the waters remained well mixed, stabilizing the environmental conditions.

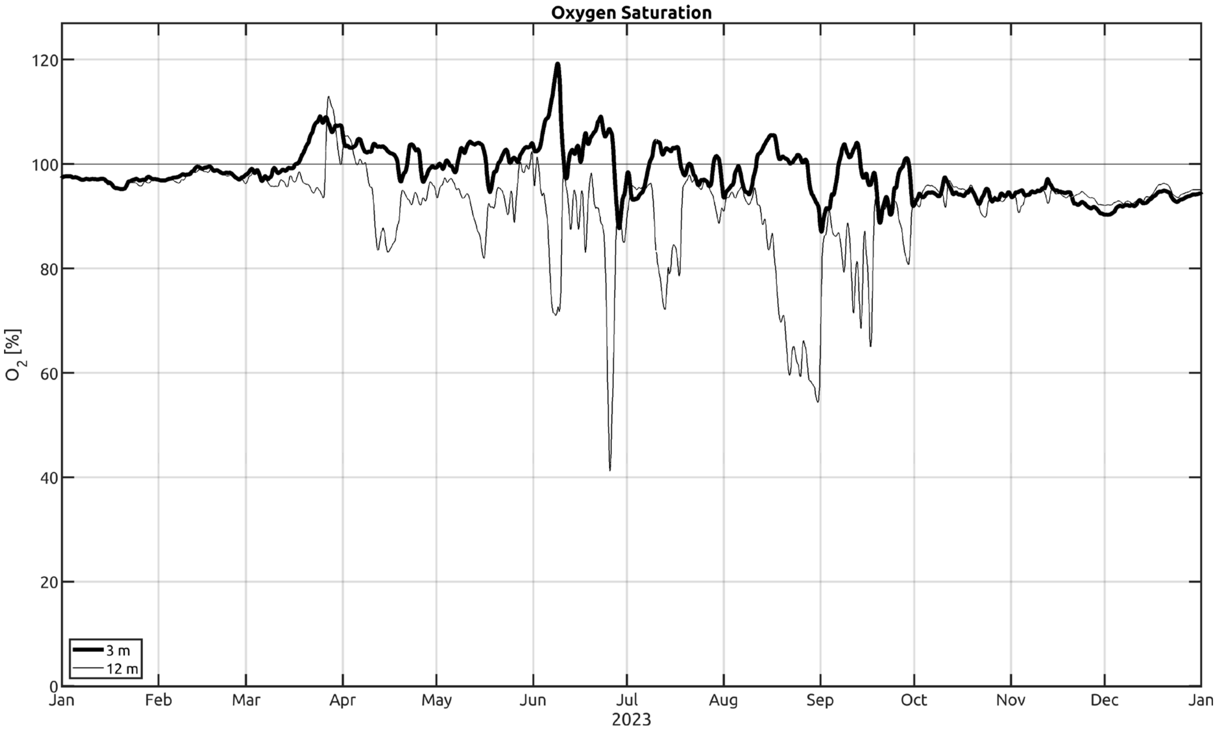


Fig. 17: Oxygen saturation measured in the surface and bottom layer at the station OB in the Pomeranian Bight in 2023.

4 Results of the routine monitoring cruises: Hydrographic and hydrochemical conditions along the thalweg

The routine monitoring cruises carried out by IOW provide the basic data for the assessments of hydrographic conditions in the western and central Baltic Sea. In 2023, monitoring cruises were performed in February, March, May, August and November. Snapshots of the temperature distribution along the Baltic thalweg transect obtained during each cruise are depicted in Fig. 18 and Fig. 19. This data set is complemented by monthly observations at central stations in each of the Baltic basins carried out by Sweden's SMHI (SMHI 2024b). Additionally, continuous time series data are collected in the Eastern Gotland Basin. Here the IOW operates three long-term moorings that monitor the hydrographic conditions in the deep-water layer. The results of these observations are given in Fig. 20 and Fig. 23.

4.1 Water temperature

The vertical temperature stratification consists of four main layers: 1. the surface layer, where the temperature is mainly determined by local heat flux between the sea surface and the atmosphere, 2. the intermediate winter water layer that conserves the winter surface temperatures till the late autumn, when the surface cooling leads to deeper mixing of the upper layer, 3. the upper deep-water layer that covers the depth range between the halocline and 120 m to 140 m depth, and 4. the deep and bottom water layer. In contrast to the surface and winter water layer, the temperature signal below the halocline is detached from the local atmospheric heat fluxes and reflects the lateral heat flows due to salt-water inflows from the North Sea and diapycnal mixing.

In the Baltic the sea surface temperature (SST) follows the annual cycle of atmospheric temperature with a phase shift of about 1 to 2 months. The winter of 2022/2023 continued a series of warm winters compared with the 30 years reference period 1991-2020, and was comparable to the previous one. January, February and March 2023 were characterized by medium to strong positive temperature anomalies of 2.5 K, 1.4 K and 1.2 K, respectively. Thus, the surface cooling of the Baltic was weaker comparing to the reference period. The sea surface temperatures remained well above the density maximum, except of the northern Baltic.

During April the mean air temperature was slightly cooler (-0.5 K) than the long-term mean. The most extreme air temperature anomalies were observed in January, June and September 2023 (see chapter 2). The air temperatures anomalies remained positive throughout the year, except for April and August. During these months the air temperature anomaly was about 0.5 K below the long-term mean. The deep-water conditions in the central Baltic remained stagnant since 2019, when the actual temperature in deep water was established by subsequent minor inflow events (MOHRHOLZ 2018).

The above average air temperature in winter 2022/23 caused a lower cooling of the surface layer than in normal years. Thus, the SST, observed in in February 2023 was relatively high at 4 °C to 4.5 °C. However, due to bad weather conditions the February cruise did not cover the Northern and Western Gotland Basin, where usually the lowest SST is observed (Fig. 18). Observations from SMHI revealed SST of 3.5 °C and 3.3 °C for the Faro Deep and Landsort Deep for that time. In the central Baltic the SST exceeded the climatological mean by 1.5 K to 1.8 K. Also, in the western Baltic the SST ranged between 4 °C at the Darss Sill and 5 °C at station TF0213 in the central Bornholm Basin. Here the climatological mean of 2.5 °C was exceeded by 2.5 K. As in the previous years the surface temperatures were well above the temperature of maximum density in the entire western and central Baltic. Therefore, the temperature driven convection was still ongoing, and no surface temperature stratification was observed in February 2023. The upper layer was homogenized down to 40 m depth in the western Baltic and to 60 m depth in the central Baltic.

The temperature distribution below the halocline is governed by the lateral inflow of saline water from the North Sea. It conserves its temperature at the time of last surface contact at the Kattegat and the Danish straits. In the late summer/autumn of 2022 some baroclinic inflows and a minor barotropic inflow transported warm saline water into the western Baltic. This inflow water spread along the thalweg and reached the eastern Bornholm Basin and the Slupsk Furrow in February 2023. It formed the warm halocline layer in the Bornholm Basin and the deep water in the Slupsk Furrow (see Fig. 18, upper panel). The core temperature for these warm waters were 10.5 °C and 10.0 °C. In December 2022 a minor barotropic inflow event carried about 57 km^3 of cool saline water into the western Baltic. In February 2023 the bottom layer in the eastern Arkona Basin and the western Bornholm Basin was covered with this cool water. Its temperature was about 6.0 °C to 6.3 °C. The tip of the inflow has reached the entrance to the Southern Gotland Basin. At the Darss Sill and in the bottom layer of the western Arkona Basin cooler water from a new inflow was visible. In the central Baltic the temperature below the halocline increased from 5.5 °C at 65 m depth to the temperature maximum of 7.27 °C at 137 m depth. At the Gotland Deep the bottom water temperature was 7.23 °C, illustrating the extremely small temperature gradient in the deep layer of the eastern Gotland Basin.

In the second half of March the sea surface temperature in the Baltic was only slightly less than in February which was mainly due to the high air temperatures in February 2023 that caused only weak surface cooling. However, the upper layer was well mixed down to the halocline. The surface temperatures ranged from 3.8 °C to 4.0 °C in the Danish straits and the Arkona Basin, which was about 1.5 K above the climatological mean. At the central station of the Bornholm Basin TF213 the SST was 4.2 °C. Towards the central Baltic the SST was decreasing to 3.2 °C in the Eastern Gotland Basin, 3.1 °C in the Fårö Deep, and 2.2 °C in the Landsort Deep. The eastward advection of saline water from minor inflows in autumn and winter controlled the temperature distribution below the surface layer. The warmer bottom water, found in the Arkona Basin in February, was completely replaced by cold water from winter inflows. This water reached also the western Bornholm Basin where it mixed up with the ambient halocline water. The patchy temperature structure below 50 m depth pointed to ongoing mixing between the particular water masses. However, the major part of the halocline water in the Bornholm Basin still consisted of high fraction of warm autumn inflow water. The temperature maximum in the Bornholm Basin was found at station TF0209 with 9.5 °C at 57 m depth. The bottom water temperature in the Basin center was 8.7 °C. Major part of the warm inflow water has moved to the eastern Slupsk Furrow, where it covered the bottom layer. Here the bottom water temperature was still above 9°C. Since February the warm water patches at the entrance of the Eastern Gotland Basin has moved northward. They followed the sea bed and arrived at 130m depth. In the Eastern Gotland Basin the temperature maximum was found at 135m depth with 7.26 °C. The bottom temperatures at station TF0271 (Gotland Deep) and in the Fårö Deep did not changed and were still at 7.23 °C and 7.17 °C.

In the first half of May the seasonal thermocline was established throughout the thalweg transect till the northern Gotland Basin. The sea surface temperatures ranged from 11.9 °C in the Kiel Bight, 9.1 °C in the Arkona Basin, 5.5 °C in the Eastern Gotland Basin, and 5.1 °C at the Landsort Deep. This was 2 to 3 K above the climatological mean values for the western Baltic, but 0.5 K below the long term mean in the central Baltic. Thus, the SST gradient along the thalweg transect was stronger than usual. In the Danish Straits and the Arkona Basin the thermocline depth was at shallow depth of 15 m to 20 m. It increases eastward to about 30 m to 35 m depth in the Eastern Gotland Basin. Below the thermocline the cold winter water became enclosed and disconnected from direct heat flux with the atmosphere. In the Bornholm Basin and the Slupsk Furrow the core temperature of winter water was 4.5 °C. It decreased significantly towards the Eastern Gotland Basin where the winter water layer depicted a core temperature of about 3.6 °C.

Below the intermediate layer the temperatures increase with depth. In the deep water of the Bornholm Basin the remains of the warm inflow waters from autumn 2022 were still visible. However, the mixing with the colder water from January inflow seemed finished, indicated by the uniform temperature distribution. The bottom water temperature in the Bornholm Basin was about 8.6 °C. In the Slupsk Furrow the deep-water conditions has changed due to the eastward spreading of cool halocline water from the Bornholm basin. This water has replaced the former warm deep water. The bottom temperature in the Slupsk Furrow has decreased to about 8.1 °C. At the overflow of the eastern sill of the Slupsk has stopped and the warm water patches observed in the Southern Gotland Basin in March were mixed up in the upper deep-water layer of the Eastern Gotland Basin. The intrusion of the warm water led to significant change of deep-water temperature of the Eastern Gotland Basin. The maximum temperature of deep water increased by 0.5 K to 7.76 °C and was found at 140 m depth. Water temperatures below 150 m depth remained unchanged at about 7.24 °C. This indicates that none of the inflowing warm plumes was dense enough to reach the bottom of the basin. The bottom water temperature in the Fårö Deep was 7.20 °C.

The fourth cruise of the Long-Term Observation Program was carried out in early August 2023, when the surface temperature in the Baltic reached its annual maximum. The temperature gradient between the surface layer and the winter water layer has strongly increased and the typical summer thermal stratification has developed throughout the Baltic Sea. The seasonal thermocline was found at depths of about 20 m in the western Baltic. In the Fehmarn Belt and the Arkona Basin the surface temperature reached 18.5 °C. Below the thermocline warm baroclinic summer inflows have replaced the former cool bottom water in the Arkona Basin. Here maximum bottom water temperature to 16.5 °C were recorded. The eastern edge of this extreme warm deep water was found in the Bornholmgat. In the Bornholm Basin an SST ranged between 12.1 °C (station TF0206) and 15.5 °C. However, the low SST in the western basin was probably caused by a coastal upwelling event. It is worth to mention, that the SST in the Bornholm Basin was about 1.5 K below the long-term mean. The thermocline in the Bornholm Basin was located at 20 m depth. Towards the central Baltic the SST increased slightly, but with high horizontal variability. At the eastern Slupsk Furrow the SST was 17.5 °C, and between 15 °C and 17 °C in the Eastern Gotland Basin which is below the climatological mean value for August.

Below the seasonal thermocline the temperature has not changed significantly in the central Baltic. Minimum temperatures in intermediate winter water layer were about 4.0 °C to 4.5 °C in the Eastern Gotland Basin, and 3.8 °C in the Northern Gotland Basin. In the Slupsk Furrow the winter water layer was slightly warmer with core temperatures of about 5.0 °C. In the Bornholm Basin only small remains of the winter water were detected. The bottom water in the basin was still covered with mixed water from the previous autumn/winter inflows. The stagnation in the deep basins of the central Baltic was ongoing. The bottom temperature in the Eastern Gotland Basin remained unchanged and was still at 7.22 °C.

The general temperature distribution in November depicted the autumnal cooling and the erosion of the seasonal thermocline in the surface layer. The seasonal surface cooling has deepened the surface mixed layer to about 40 m to 45 m. However, due to extremely warm September the surface temperatures were at a high level. In the Fehmarn Belt and at the Darss Sill surface temperatures ranged from 11.3 °C to 11.5 °C, already 2 K higher than the climatological mean. Except a slightly cooler region in the western Bornholm Basin the SST in the central Baltic was at or above 10 °C, which was about 2 K higher than normal. In the Eastern Gotland Basin the SST was 10.2 °C, at station TF0271. The deepening of the seasonal thermocline eroded the winter water layer and reduced its thickness to about 15 m to 20 m, with minimum temperatures of 4.5 °C in the Eastern Gotland Basin. In the Bornholm Basin and in the Slupsk Furrow no remains of intermediate winter water were found. From the Belt Sea to the Arkona Basin the bottom water was significantly warmer than the surface water layer. The warm baroclinic summer inflows covered the bottom water layer. The bottom layer of the Arkona Basin depicted a maximum deep-water temperature of 14.6 °C. The warm inflow waters covered the halocline layer in the Bornholm Basin between 50 m and 70 m depth. Its core temperature was 11.6 °C at station TF0213. The inflow waters have also completely flushed the deep-water layer of the Slupsk Furrow. Here the bottom temperature increased to 10.2 °C. Maximum deep-water temperature in the Slupsk Furrow was 10.7 °C which was found at 68 m depth. Parts of the warm inflow waters have spread over the eastern sill of the Slupsk Furrow and reached the southern Gotland Basin. Here a warm water plume was detected at the bottom between 100 m and 120 m depth. Its core temperature was about 9 °C. The deep-water temperature conditions in the Gotland Basin remained still unchanged, with the maximum temperature of 7.38 °C at 140 m depth and bottom temperature of 7.22 °C at station TF0271. Due to bad weather conditions in November 2023 only a few stations could be operated in the Northern Gotland Basin.

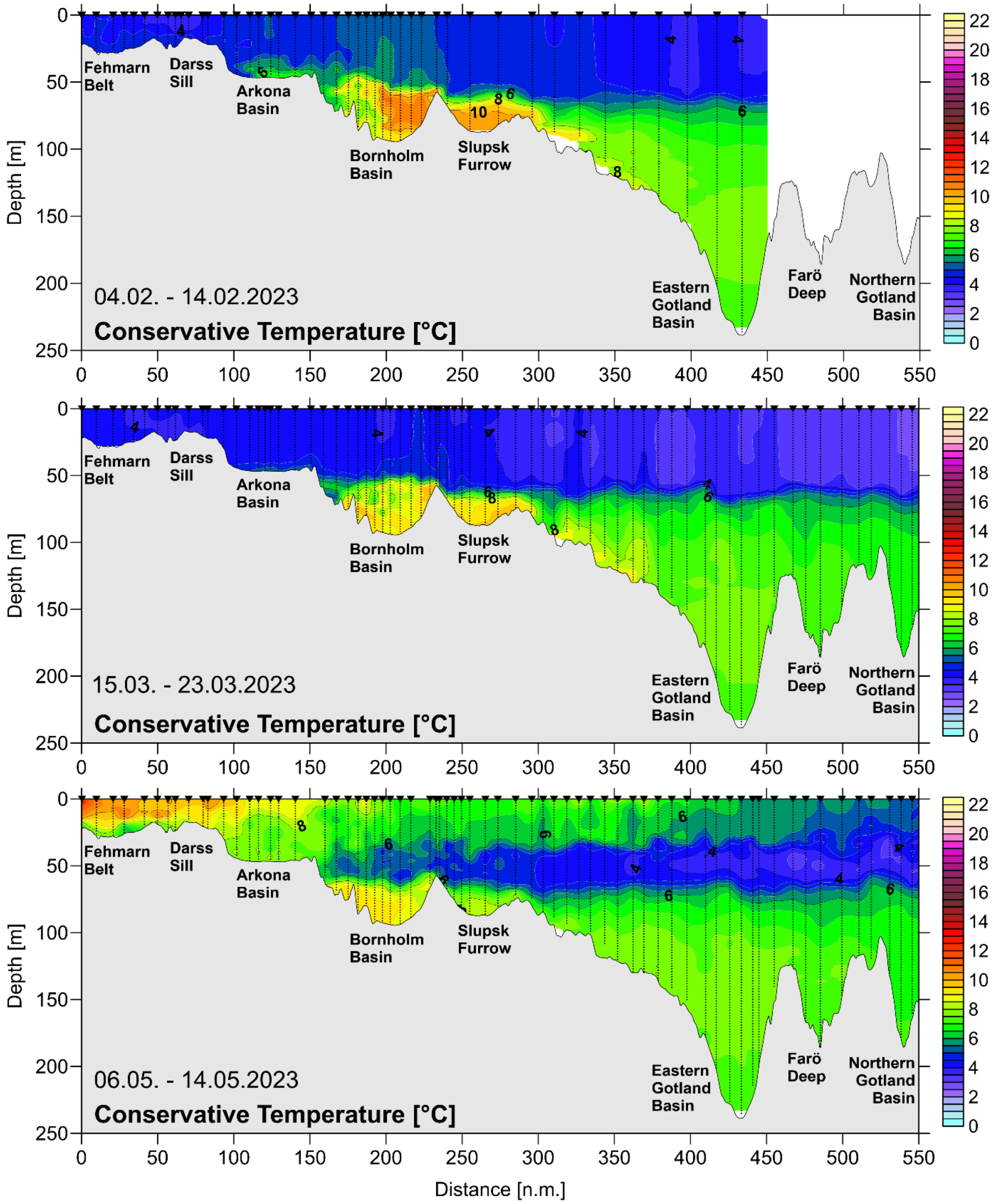


Fig. 18: Temperature distribution along the thalweg transect through the Baltic Sea between Darss Sill and Northern Gotland Basin for February, March, and May 2023.

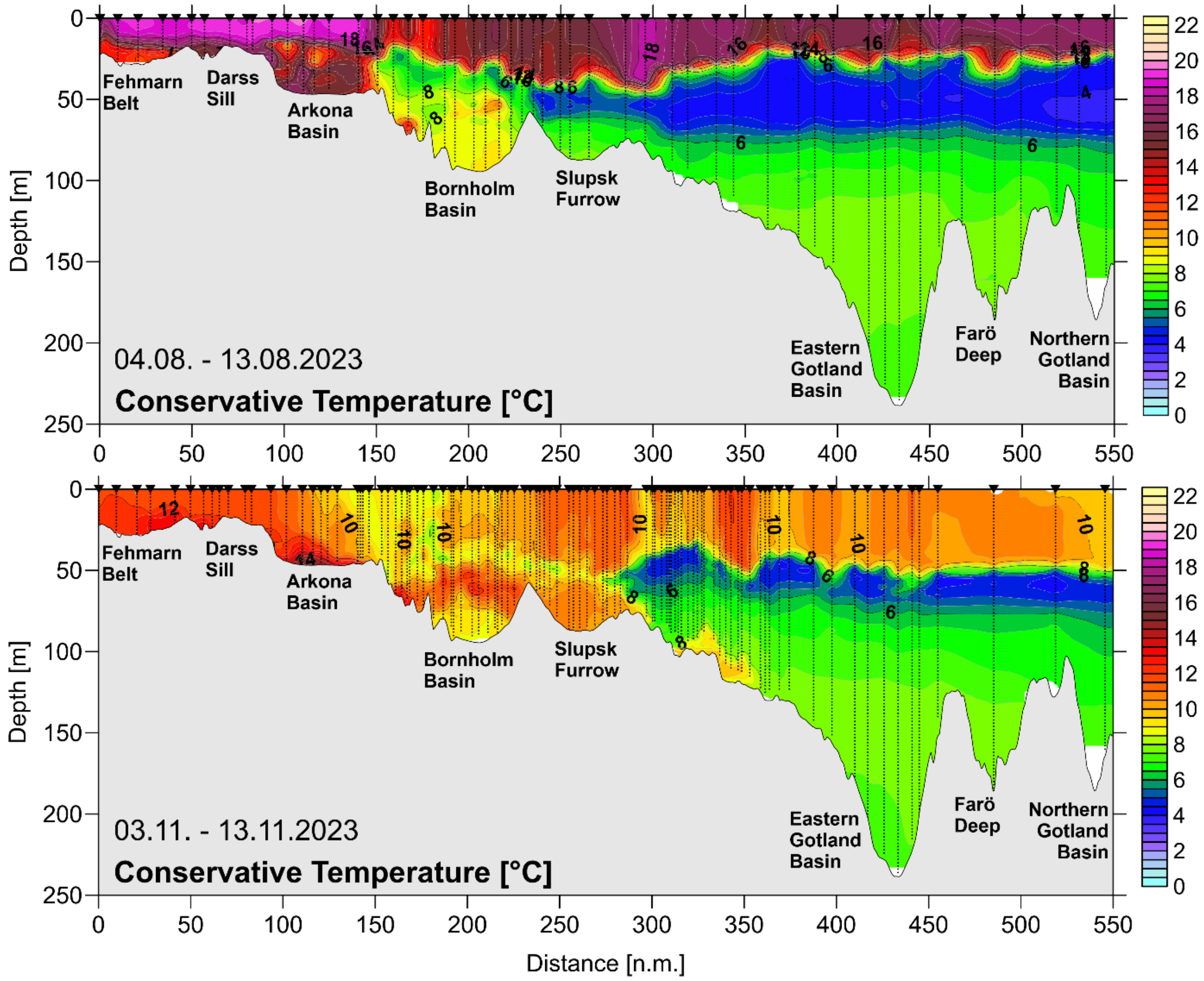


Fig. 19: Temperature distribution along the thalweg transect through the Baltic Sea between Darss Sill and Northern Gotland Basin for August and November 2023.

As part of its long-term monitoring programme, IOW operates hydrographic moorings in the Eastern Gotland Basin. The mooring at the basin near station TF271 is operational since October 2010. In contrast to the Gotland Northeast mooring, operational since 1998 and from where the well-known 'Hagen Curve' (FEISTEL et al. 2006, NAUMANN et al. 2017) is derived, the mooring at TF271 also collects salinity and oxygen data. The gathered time series data allow the description of the development of hydrographic conditions in the deep-water range (140 m depth to bottom) of the Gotland Basin in high temporal resolution. This time series greatly enhances the IOW's ship-based monitoring programme. Figure 20 shows the temperature time series at the five depth levels in the deep water gathered between January 2022 and December 2023. In the year 2022 the temperature stratification in the deep water was characterized by extremely low variability. The temperature was decreasing towards the bottom, although the vertical temperature gradient of 0.3 mK m^{-1} is rather weak. This gradient was further decreasing until January 2023, when the temperature difference between 140 m depth and the bottom was only 0.2 K. Then the first indication of intrusions appeared at the 140 m depth level. In mid April 2023 the major part of warmer intrusion reached the 140 m depth level and soon after also the 160 m depth level. After a first increase the temperature at 140 m decreased slowly by about 0.15 K until December 2023. In contrast, at 160 m depth the temperature was slowly rising during that time. The water below 160 m depth were not reached by the warm intrusions. There the temperature remained at a constant level with an extremely weak vertical gradient. The recent inflow events carried warm water into the upper deep-water layer, but were not dense enough to reach the deep layers of the Eastern Gotland Basin. The period of relatively warm deep-water conditions was continued in 2023.

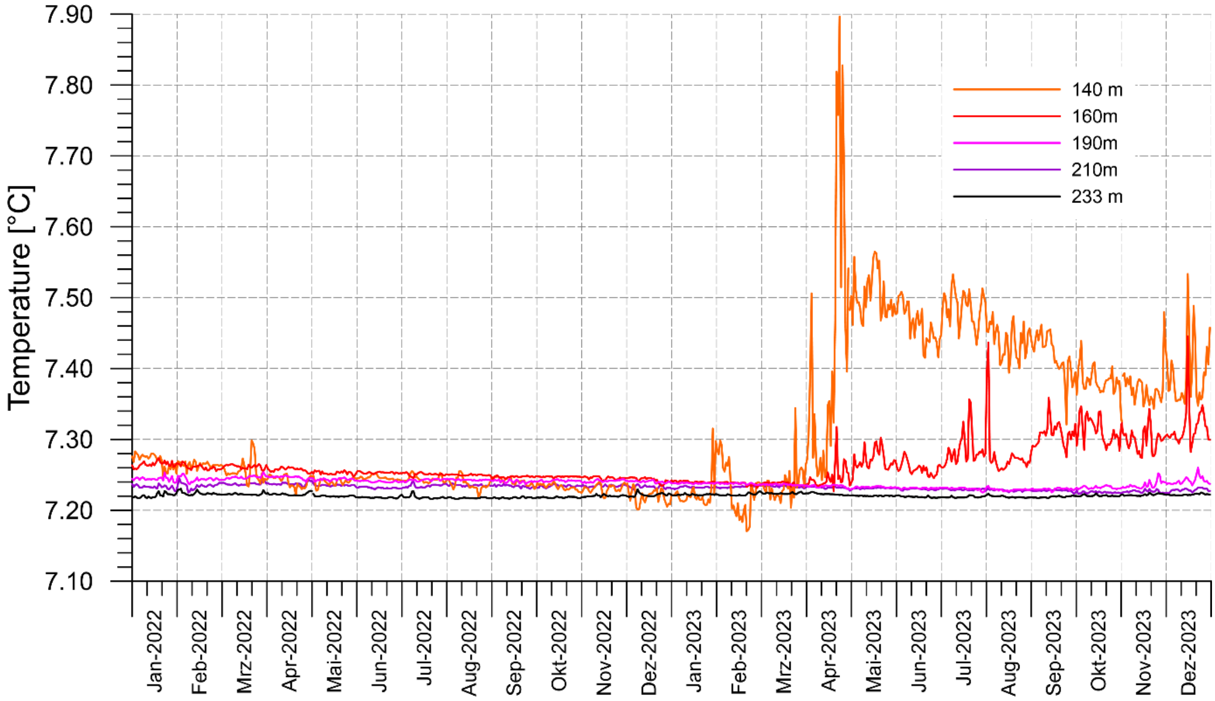


Fig. 20: Temporal development of deep-water temperature in the Eastern Gotland Basin (station TF0271) from January 2022 to December 2023 (daily averages of original data with 10 min sampling interval).

Table 4.1 summarises the annual means and standard deviations of temperature in the deep water of the central Baltic based on CTD measurements over the past five years. The deep-water temperatures in the entire Baltic remained nearly constant since 2022, with the exception of the shallower Bornholm Deep and Karlsö Deep. The weak increase of 0.02 K at 150 m depth in the Fårö Deep can be attributed to overflow of upper deep-water from the Eastern Gotland. The moderate increase in the Bornholm Basin was caused by the baroclinic inflows in summer /autumn 2023. The high standard deviation of 0.88 K indicates by the active inflow dynamic of baroclinic and minor barotropic inflows.

Table 4.1: Annual means and standard deviations of deep-water temperature in the central Baltic Sea, based on IOW- and SMHI data (n= 14-25, unit °C; maximum in bold).

Station	Depth m	2019	2020	2021	2022	2023
213 (Bornholm Deep)	80	8.65 ±0.12	8.45 ±0.29	8.42 ±0.39	8.43 ±0.94	**9.09 ±0.88**
271 (Gotland Deep)	200	7.20 ±0.07	7.21 ±0.01	7.23 ±0.00	**7.24 ±0.00**	7.23 ±0.00
286 (Fårö Deep)	150	7.05 ±0.18	7.24 ±007	**7.24 ±001**	7.18 ±0.01	7.20 ±0.07
284 (Landsort Deep)	400	6.37 ±0.15	6.60 ±0.27	**6.67 ±0.02**	6.57 ±0.02	6.56 ±0.09
245 (Karlsö Deep)	100	5.64 ±0.12	5.83 ±0.11	**6.05 ±0.11**	6.04 ±0.09	5.88 ±0.15

4.2 Salinity

The vertical distribution of salinity in the western and central Baltic Sea during IOW's five monitoring cruises is shown in Fig. 21 and Fig. 22. The salinity distribution is markedly less variable than the temperature distribution, and a west-to-east decreasing gradient in the surface and the bottom water is typical. Greater fluctuations in salinity are observed particularly in the western Baltic Sea where the influence of salt-water inflows from the North Sea is strongest. The duration and influence of minor inflow events is usually too small to be reflected in the overall salinity distribution. Only combined, they can lead to slow, long-term changes in salinity. The salinity distributions shown in Fig. 21 and Fig. 22 are mere 'snapshots' that cannot provide a complete picture of inflow activity. In 2023 the evolution of salinity distribution was mainly controlled by the minor barotropic inflow in December 2022 and the baroclinic inflows in late summer to autumn. However, the IOW monitoring cruises covered the inflows only partly. The salinity at the Darss Sill exceeded the 17 g kg^{-1} level only in August. It is not possible to produce meaningful statistics on inflow events, by using only the monitoring cruises. The analyses of the sea level changes and the salinity observations in the western Baltic revealed a weak barotropic inflow activity in the winter season 2022/2023. Only one weak barotropic inflow was detected in December 2022, which transported about 1.2 Gt salt into the western Baltic. During summer and autumn 2023 baroclinic inflows dominated the water exchange with the North Sea. However, also two minor barotropic inflows were observed in June and end of July that transported together about 1.4 Gt salt into the Arkona Basin.

The first monitoring cruise in 2023 was performed about a month after the moderate inflow in December. Saline waters of this inflow were still covering the bottom layer in the Arkona Basin where maximum bottom salinity of 21.4 g kg^{-1} was observed. Above this high saline layer of only 3 m to 4 m thickness a second 10 m thick layer with moderate salinity of 12 g kg^{-1} to 16 g kg^{-1} was found. In the Fehmarn Belt high saline water indicated a new but minor inflow that has not reached the Darss Sill. There the bottom salinity was only 12.0 g kg^{-1}. The surface layer above the Darss Sill was covered by brackish Baltic surface water with a salinity of 8.0 g kg^{-1}. In the Bornholm Basin the halocline depth was at 55 m, corresponding to the sill depth of the Slupsk Sill. However, there were signs of an active overflow of the sill caused by a local uplift of the halocline in the eastern Basin. The salinity in the deep-water layer of the Bornholm Basin increased continuously to a bottom salinity of 17.0 g kg^{-1}. The Slupsk Furrow depicted relatively uniform deep waters. The bottom salinity was 13.6 g kg^{-1} here. North of the Slupsk Furrow only a few CTD stations could be conducted due to bad weather conditions. The halocline in the Eastern Gotland Basin was located at 61 m depth. The bottom salinity was 12.83 g kg^{-1} at station TF0271.

The general situation did not change significantly to the next cruise in March 2023. No inflow signals were detected in the Belt Sea. At the Darss Sill no saline bottom layer was found. Here the brackish surface water covered the entire water column. The thin saline bottom layer in the Arkona Basin was still present, but with reduced thickness. The maximum bottom salinity was 18.6 g kg^{-1} at station TF0113. The halocline depth was found at 37 m. The major part of the saline deep water has left the Arkona Basin through the Bornholmgat as seen in the temperature distribution. It changed the stratification in the Bornholm Basin moderately. The bottom salinity in the Bornholm Basin decreased to 16.5 g kg^{-1}. Parts of the halocline waters have crossed the Slupsk Sill and reached the Slupsk Furrow. Here the halocline depth was still well above the depth of the eastern sill. Thus, there was an active overflow observed, that transported warm saline water into the southern Gotland basin. Patches of this water are indicated at the thalweg transect by bottom waters with salinity of about 12 g kg^{-1}. However, these waters did not reach the deep layers in the central Baltic. As in the recent years the salinity in the deep water of the central Baltic Sea decreased continuously. The bottom salinity in the Gotland Deep was 12.81 g kg^{-1}. The 12 g kg^{-1} isohaline was at a depth of around 140 m, 7 m deeper as observed one year before, pointing to the continuous salt loss of the deep water by weak vertical mixing. Further north in the Fårö Deep the bottom salinity was 12.06 g kg^{-1}, nearly 0.10 g kg^{-1} less than one year before.

In May 2023 the salt distribution in the Fehmarn Belt and at the Darss Sill depicted a strong stratification. However, the bottom salinity was only 18.5 g kg^{-1} in the Fehmarn Belt. The brackish surface water indicated a typical outflow situation. At the Darss Sill, the bottom salinity was only 12.5 g kg^{-1}. The saline bottom water pool in the Arkona Basin nearly vanished. The halocline was found at 40 m depth in the centre of the basin. The bottom salinity amounted to 15.8 g kg^{-1} only. In the Bornholm Basin the salinity distribution did not change compared to March. Further east in the Slupsk Furrow the saline bottom water pool was significantly reduced, although there were still indications of a weak overflow into the Southern Gotland Basin. No significant changes of deep-water conditions were observed in the central Baltic.

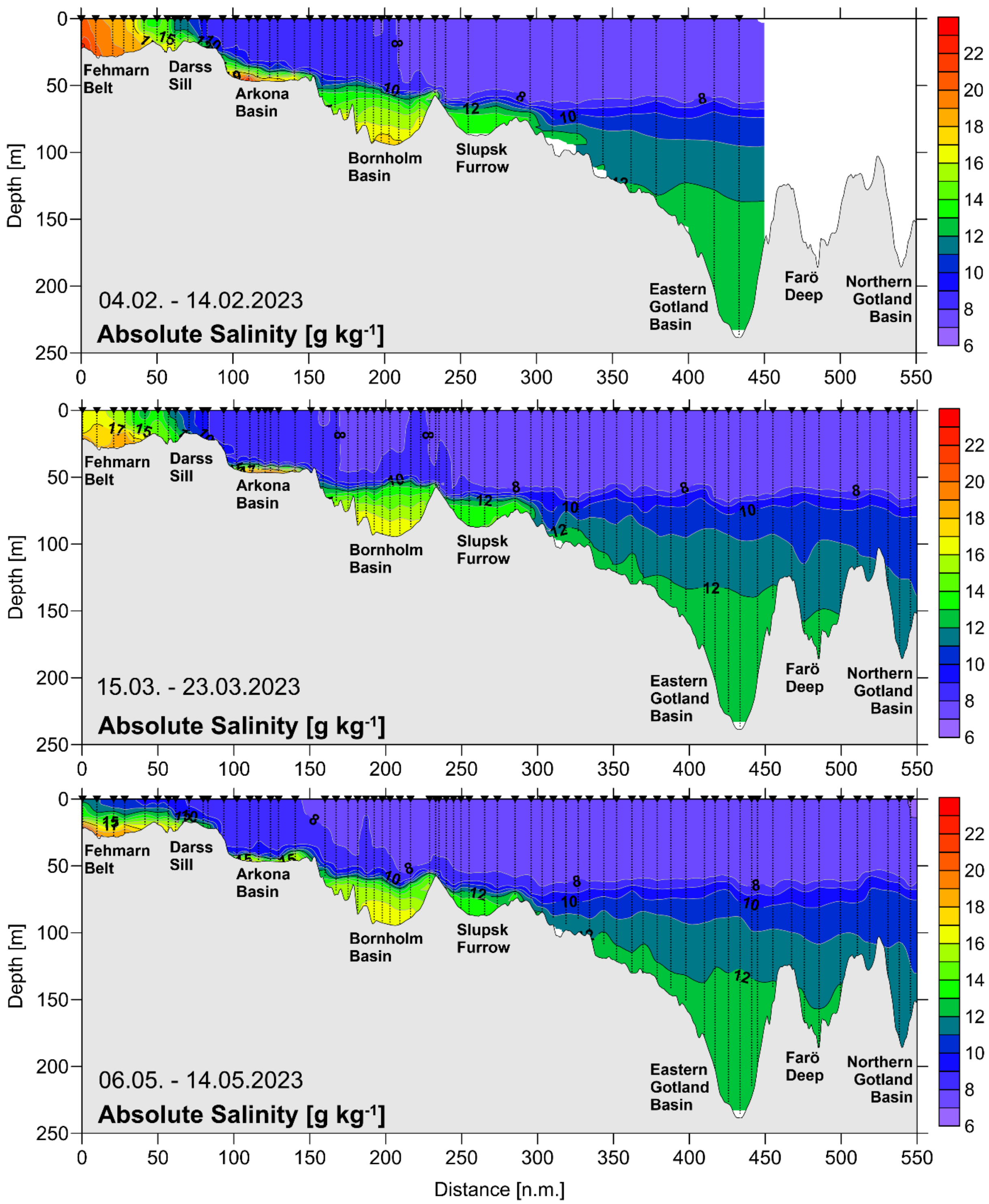


Fig. 21: Salinity distribution along the thalweg transect through the Baltic Sea between Darss Sill and Northern Gotland Basin for February, March, and May 2023.

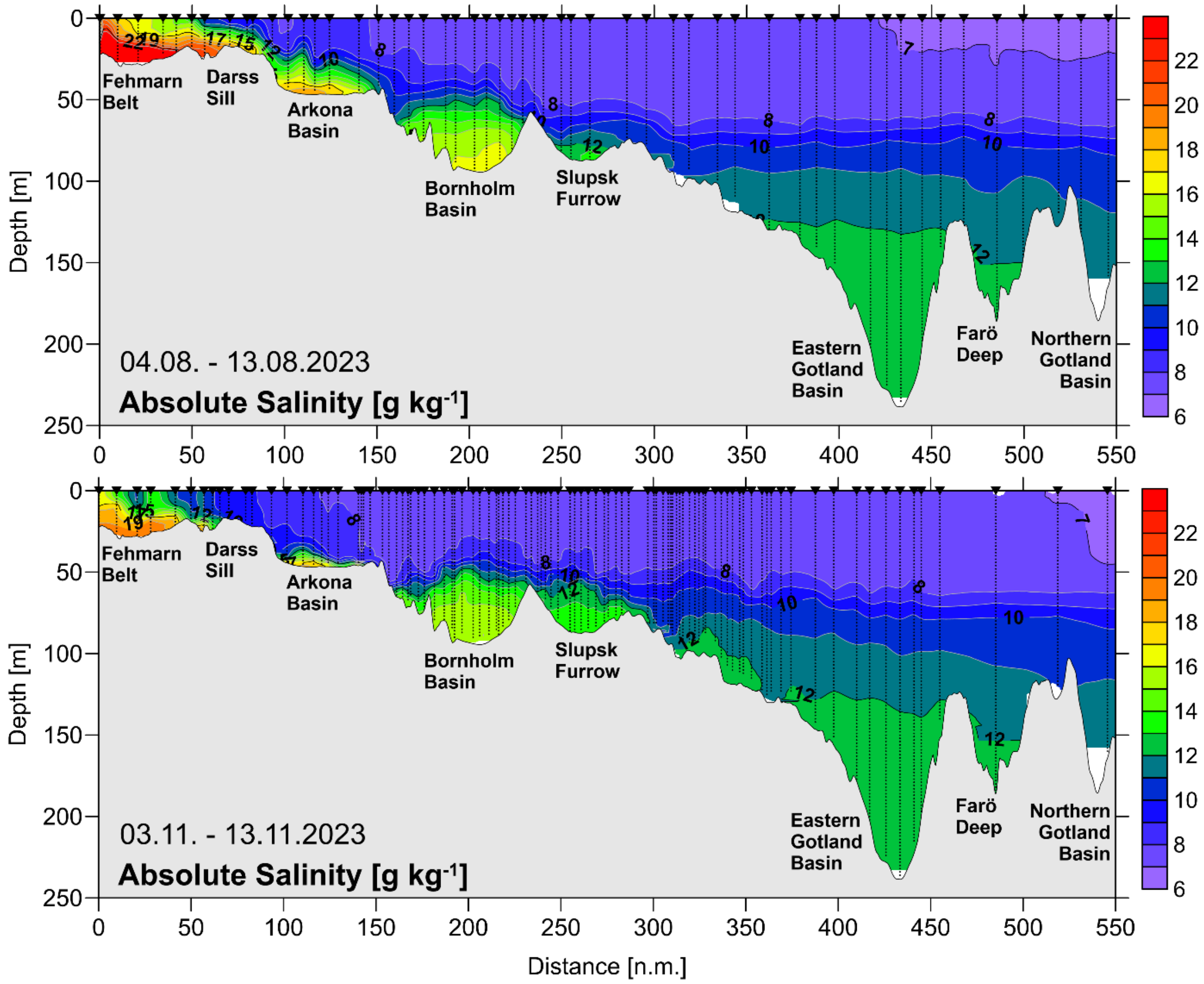


Fig. 22: Salinity distribution along the thalweg transect through the Baltic Sea between Darss Sill and Northern Gotland Basin for August and November 2023.

Significant changes in the salinity distribution in the western Baltic were detected during the cruise in August 2023. The observations depicted the ongoing of baroclinic inflows through the Belt Sea. In the Fehmarn Belt a 10 m thick bottom layer with salinity of 28.4 g kg^{-1} was found. The maximum bottom salinity of 28.6 g kg^{-1} was detected at station TF0361 west of Fehmarn. At the Darss Sill the salinity increased from 8.9 g kg^{-1} at the surface to 17.2 g kg^{-1} near the bottom, with a main halocline at 6 m depth. The Arkona Basin was filled with extreme warm and saline water from the halocline at about 15 to 20 m depth to the bottom. Here a temperature and salinity of 16.4 °C and 18.6 g kg^{-1} were measured. This bottom salinity was relatively low compared with barotropic inflow situations, when the water with highest salinity originates from the Öresound. In contrast, baroclinic inflows spread only through the Beltsea. The tip of the inflowing saline water has passed the Bornholmgat, and spread into the western Bornholm Basin. Here the halocline depth has lifted up by about 10 m to 45 m depth. However, the deep-water layer was not reached at the time of the observations. At station TF0213 the bottom salinity remained at 16.2 g kg^{-1}, nearly the same value as in March. The salinity in the Slupsk Furrow has significantly decreased since spring, mainly due to flushing with less saline water, originating from the upper halocline in the Bornholm Basin. The bottom salinity was 12.8 g kg^{-1}. Further east, in the central Baltic basins, the saline plumes from the previous inflow season were mixed up in the upper deep-water layer above 160 m depth. The saline water surplus lifted the 12 g kg^{-1} isohaline in the

Eastern Gotland Basin by 5 m to 135 m depth. The bottom salinity in the Gotland Deep was 12.77 g kg^{-1}, which was only 0.04 g kg^{-1} less than in March. In the Fårö Deep the bottom salinity remained unchanged at 12.07 g kg^{-1}. The surface salinity in the central Baltic decreased according its usual seasonal cycle, and was at 6.8 g kg^{-1} in the Eastern Gotland Basin.

The baroclinic inflows continued also in September, due to the unusual calm and warm weather conditions. The results of this inflow are impressively seen in the temperature distributions depicted in Fig. 19. In the Fehmarn Belt the baroclinic stratification was still present in November, although the bottom salinity has significantly decreased to 18.9 g kg^{-1}. However, at the Darss Sill brackish Baltic surface water covered the entire water column, pointing to an outflow situation. The saline bottom pool in the Arkona Basin has lost most of its volume compared to August. Only a thin layer above the bottom depicted a higher salinity. Its maximum of 17.7 g kg^{-1} was found in the basin center. The thickness of the saline bottom layer decreased towards the Bornholmgat. The water from the baroclinic summer and autumn inflows covered the entire halocline of the Bornholm Basin. The halocline in the Bornholm Basin was lifted up to 40 m at station TF0213. However, the inflow water was not dense enough the replace the bottom water layer in the Bornholm Basin. The bottom salinity was 15.8 g kg^{-1} here. Due to its large volume the inflow water has already passed the Slupsk Sill and has completely flushed the deep and halocline layer of the Slupsk Furrow. This process increased the salinity in the bottom water pool of the Slupsk Furrow to 12.5 g kg^{-1}. First plumes of the inflow water also reached also the Southern Gotland Basin. The stagnation in the deep water of the central Baltic was still ongoing. The bottom salinity decreased very slowly in the Gotland Deep and the Fårö Deep to 12.72 g kg^{-1} and 12.05 g kg^{-1}.

Table 4.2 shows the overall trend of salinity in the deep water of the Baltic in the past five years. After the series of stronger inflow events in 2014 to 2016 the bottom salinity in the Gotland Deep and Fårö Deep reached its maxima in 2016 and 2017. Since than only weak changes in salinity stratification were observed in the central Baltic. The deep-water salinity in the Eastern Gotland Basin dropped slightly due to vertical mixing by 0.10 g kg^{-1} to 0.15 g kg^{-1} per year. In the Fårö Deep the annual salinity decrease was slightly higher up to 0.20 g kg^{-1}. In the Karlsö Deep and Landsort Deep the slow decrease of deep-water salinity has also continued. In the Bornholm Basin the mean deep-water salinity increased due to the barotropic inflow event in early 2023. The drop in deep-water salinity of the Bornholm Basin do not point to an overall trend.

No clear trend was visible in the surface salinity of the Baltic. It was nearly constant, with exception of the Fårö Deep where the SST increased by 0.2 g kg^{-1}. Table 4.3 summarises the variations in surface layer salinity.

Table 4.2: Annual means and standard deviations of deep-water salinity in the central Baltic Sea, based on IOW- and SMHI data (n= 14-25, unit g kg⁻¹; maximum in bold).

Station	Depth m	2019	2020	2021	2022	2023
213 (Bornholm Deep)	80	**16.63 ±0.27**	16.34 ±0.34	15.84 ±0.26	15.03 ±0.36	15.54 ±0.48
271 (Gotland Deep)	200	**13.16 ±0.03**	13.03 ±0.03	12.93 ±0.03	12.77 ±0.03	12.68 ±0.04
286 (Fårö Deep)	150	**12.46 ±0.08**	12.39 ±0.03	12.24 ±0.08	12.02 ±0.03	11.87 ±0.05
284 (Landsort Deep)	400	11.33 ±0.06	**11.34 ±0.16**	11.24 ±0.06	10.94 ±0.02	10.87 ±0.09
245 (Karlsö Deep)	100	10.35 ±0.24	**10.40 ±0.18**	10.36 ±0.18	10.26 ±0.12	10.06 ±0.21

Table 4.3: Annual means and standard deviations of surface water salinity in the central Baltic Sea for the years 2019 to 2023 (minimum values in bold, n= 14-25). The long-term averages of the years 1952-2005 are taken from the BALTIC climate atlas (FEISTEL et al. 2008).

Station	1952-2005	2019	2020	2021	2022	2023
213 (Bornholm Deep)	7.60 ±0.29	7.63 ±0.11	7.80 ±0.18	**7.54 ±0.26**	7.66 ±0.06	7.57 ±0.22
271 (Gotland Deep)	7.26 ±0.32	7.19 ±0.25	7.33 ±0.16	7.36 ±0.13	**7.17 ±0.25**	7.18 ±0.25
286 (Fårö Deep)	6.92 ±0.34	**6.78 ±0.33**	7.07 ±0.29	7.12 ±0.23	6.85 ±0.39	7.04 ±0.25
284 (Landsort Deep)	6.75 ±0.35	6.52 ±0.26	6.58 ±0.50	**6.33 ±0.33**	6.58 ±0.28	6.53 ±0.24
245 (Karlsö Deep)	6.99 ±0.32	6.89±0.24	7.16 ±0.12	**6.86 ±0.25**	6.98 ±0.31	6.96 ±0.12

Fig. 23 depicts the temporal development of salinity in the deep water of the Eastern Gotland Basin between January 2022 and December 2023, based on the observations from the hydrographic mooring at the Gotland Deep. The stratification in this period was again controlled by stagnation and weak vertical mixing. This led to a slowly decreasing salinity in the entire deep-water body, with a nearly constant vertical salinity gradient below 160 m depth. The higher temporal variability in the 140 m and 160 m depth levels was caused by pulse like intrusions of saline water plumes from minor inflow events into the halocline. Below 160 m depth the rate of salinity decrease was about 0.125 g kg^{-1} per year, which is equal to 1 g kg^{-1} in eight years. It will take another 7 years to reach the bottom water salinity observed before the extreme MBI of 2014.

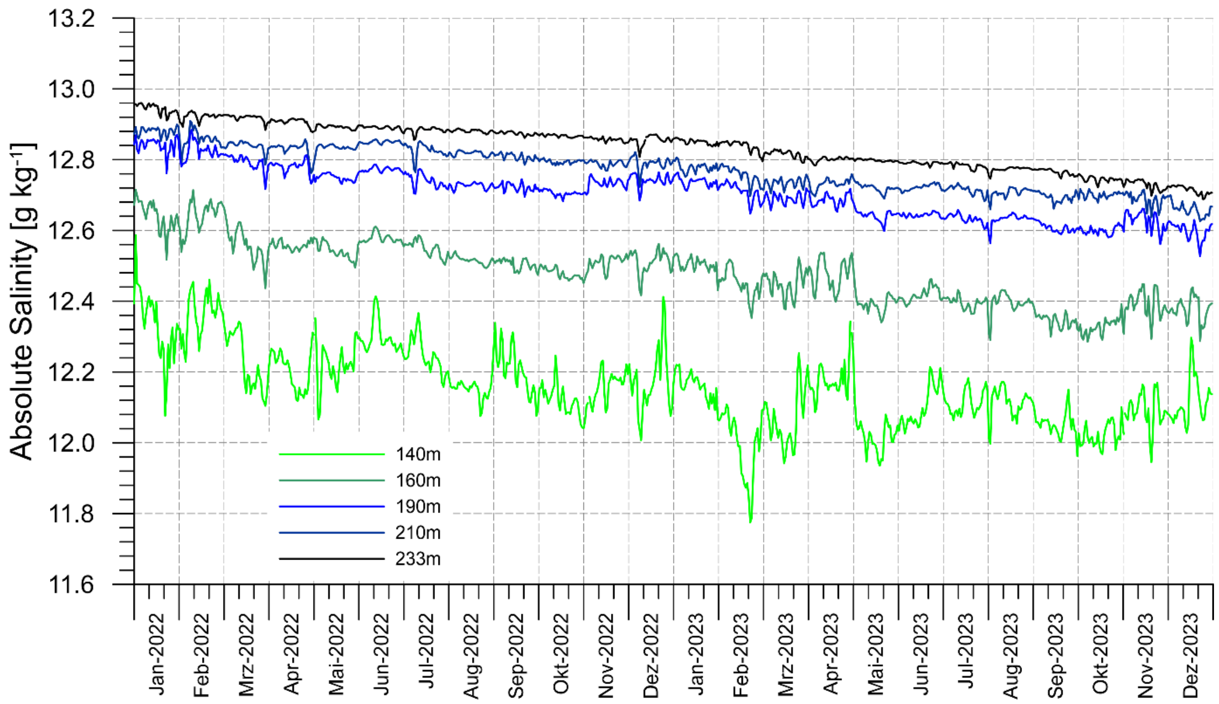


Fig. 23: Temporal development of deep-water salinity in the Eastern Gotland Basin (station TF0271) from January 2022 to December 2023 (Daily averages of original data with 10 min sampling interval).

4.3 Oxygen distribution

The eutrophication of Baltic Sea waters over several decades (HELCOM 2023) resulted in an intensified deficit of oxygen in deep and bottom waters. This is a well observed situation in the Baltic Sea deep basins, but in recent years it became more and more clear that also shallow Baltic Sea areas are increasingly subjected to temporally low oxygen values. This phenomenon is surprising, as deep mixing in winter of each year oxygenates the water column in shallow sea areas until the bottom. However, during summer the microbial decomposition of large amounts of organic matter requires considerable amounts of the present oxygen. In surface waters as well as in shallow areas, the gas exchange with the atmosphere maintains an oxygen concentration of seawater controlled by the surface water temperature. This includes emission of oxygen by the sea during primary production in spring as well as uptake of oxygen during elevated remineralisation activity in summer and autumn (KUSS et al. 2006). When a stable thermocline developed in addition to the usually present halocline, oxygenated surface water was efficiently separated from the water below. Then, the oxygen concentration clearly declines by respiration in bottom water that could not be replenished during summer. Strong temperature and/or salinity gradients hinder mixing between the bottom water body and upper water. So, lasting oxygen consumption during calm weather condition at summer water temperatures could threaten the ecosystem near the seafloor. To observe and finally to recommend measures, the bottom water oxygen concentration in shallow areas is for the first time assessed for test purposes during HOLAS III (HELCOM "Third Holistic Assessment of the Ecosystem Health of the Baltic Sea") by an indicator based on the long-standing application of the "Iltsvind" (Oxygen loss) model for the western Baltic Sea, proposed by the Danish party in HELCOM.

For the Baltic Sea deep basins, it is a natural phenomenon that oxygen supply is coupled to the entrainment of dense North Sea water, which is hindered by the shallow and narrow transition area between the North Sea and the central Baltic Sea. Although an almost permanent slow entrainment of oxygenated water to the central Baltic Sea happens, only episodic strong inflows of cold and haline oxygenated water, known as “Major Baltic Inflows" reach the bottom water of the deep Baltic basins. The improvement is mainly determined by the amount of supplied oxygen and the density of the water. However, the effect of the strong MBI series during 2014-2016 basically vanished already in 2017 and the water below the permanent halocline turned into anoxic and then to euxinic conditions again. This is in principle caused by the elevated density of the deep water after the MBI, initially hindering further MBIs. But the fast consumption of oxygen by mineralization of unprecedented enormous amounts of accumulated organic matter and reducing chemical species, mainly ammonium and hydrogen sulphide, appears to be a phenomenon of recent times. After oxygen depletion, other oxidants are used. Sulphate, a major constituent of seawater is converted to poisonous hydrogen sulphide that turns Baltic Sea deep water into dead zones for aerobic life. This process is fostered by eutrophication and subsequent excessive supply of organic matter to the seafloor (DIAZ & ROSENBERG 2008). The lack of oxygen below the halocline of the Baltic Sea areas is evaluated by using the HELCOM oxygen debt indicator for the deep basins to estimate the deviation from a “good environmental status” (HELCOM 2013).

We now generally use µmol l^{-1} as the standard unit for oxygen concentration. The oxygen concentration could be converted from µmol l^{-1} to ml l^{-1} by the factor 0.0223916 ml µmol^{-1} (HELCOM 2020).

The overall decreasing trend of the oxygen concentration, in fact an accumulation of hydrogen sulphide expressed as negative oxygen concentration in deep water of the Gotland Deep, the Fårö Deep and the Karlsö Deep was ongoing (Table 4.4 - oxygen). At Gotland Deep station, the decline of oxygen continued since 2019 (-111 µmol l^{-1}) and showed in 2023 an accumulation of hydrogen sulphide equivalent to -317 ml/l oxygen at the 200 m reference depth. At Fårö Deep station in 150 m depth, oxygen decreased since 2019 from -78 µmol l^{-1} to -171 µmol l^{-1} oxygen in 2023.

Table 4.4: Annual means of 2019 to 2023 with standard deviations of oxygen concentration in the deep water of the central Baltic Sea (in µmol l^{-1}, IOW and SMHI data); hydrogen sulphide is expressed as negative oxygen equivalents; maxima in bold).

Station	Depth m	2019	2020	2021	2022	2023
213 Bornholm Deep	80	43.3 ±67.0	39.7 ±59.8	7.6 ±41.1	1.3 ±46.1	**44.4 ±69.0**
271 Gotland Deep	200	**-110.8 ±52.7**	-184.4 ±58.1	-188.8 ±17.2	-242.4 ±30.6	-317.1 ±119.6
286 Fårö Deep	150	-77.7 ±18.3	**-63.4 ±28.6**	-94.6 ±17.8	-122.9 ±74.8	-171.3 ±83.9
284 Landsort Deep	400	**-66.5 ±11.2**	-97.8 ±20.1	-74.0 ±4.2	-98.2 ±16.7	-90.4 ±26.0
245 Karlsö Deep	100	**-87.1 ±55.8**	-101.8 ±29.0	-92.4 ±38.2	-108.5 ±39.4	-146.2 ±135.4

However, as the standard deviation was about 50 %, the considerable variability indicated some short-term improvements at this site during the last years. Also in the western Gotland Basin a general deceasing trend of the oxygen concentration could be notified. However, at Landsort Deep the oxygen equivalent concentration of hydrogen sulphide decreased from -67 µmol l^{-1} in 2019 to -98 µmol l^{-1} in 2020, improved to -74 µmol l^{-1} in 2021, declined to -98 µmol l^{-1} in 2022 and improve a bit to -90 µmol l^{-1} oxygen equivalents of hydrogen sulphide in 2023. At Karlsö Deep the oxygen concentration declined from -87 µmol l^{-1} in 2019 to -146 µmol l^{-1} in 2023, but recovered in 2021 to -92 µmol l^{-1} at the 100 m reference depth of this site (Table 4.4). It also indicated by the given standard deviation that considerable variability during 2023 occurred at this site. The choice of an individual reference depths in the middle of the respective deep water thereby secures annual averages that are basically unbiased from episodic smaller inflows in the depth range of the pycnocline and pore water exchange from the sediment in the near bottom layer, but vanish soon. Bornholm Deep more frequently received oxygenated water from the Arkona Basin and flipped from weak euxinc to slightly oxic conditions during the years. Even in summer and autumn at higher temperatures, the density is often high enough to entrain the Bornholm Sea deep water. The annual average oxygen concentration since 2019 changed between the detection limit of 1 µmol l^{-1} and almost 45 µmol l^{-1} and thus indicated a dominantly oxic situation in recent years at this site (Table 4.4).

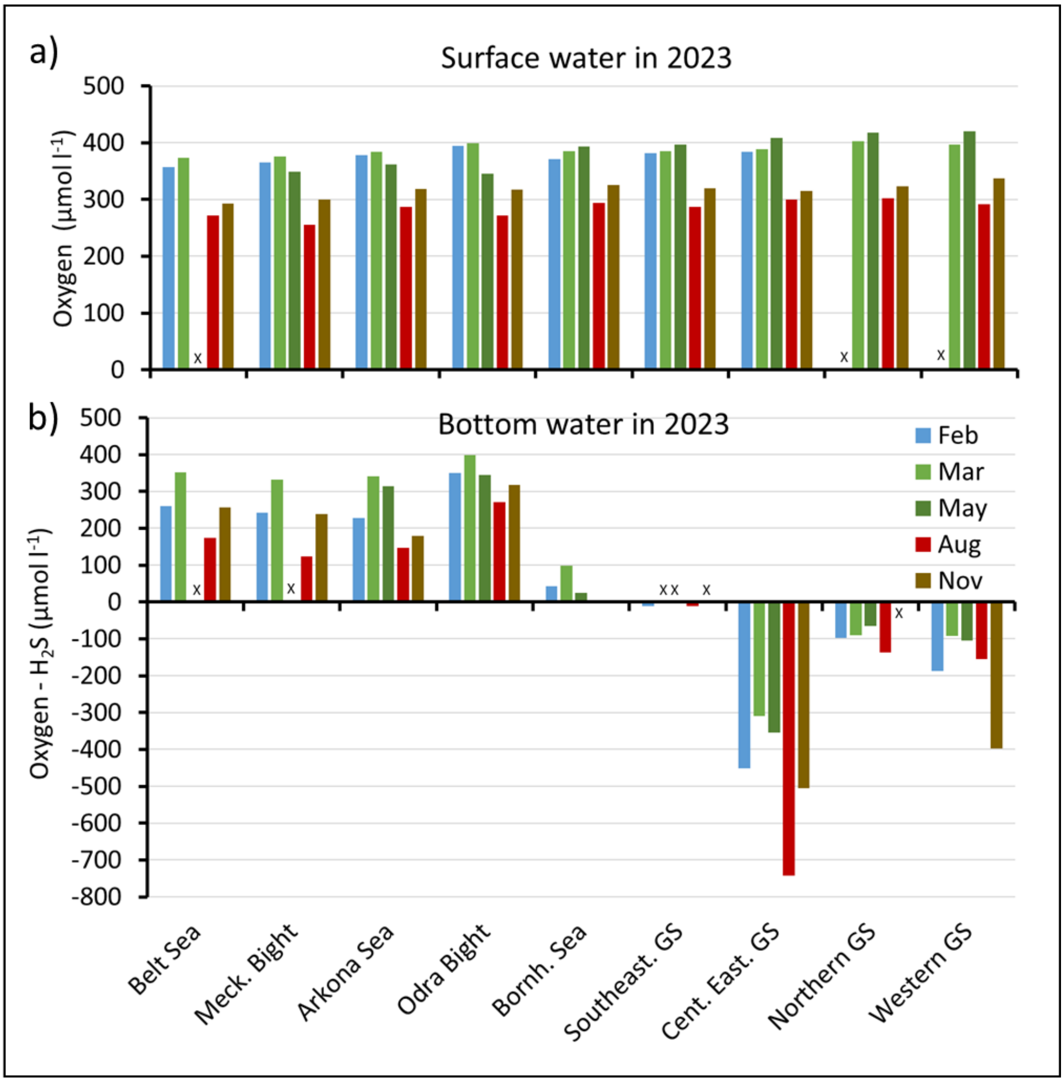


Fig. 24: Comparison of average oxygen concentrations a) in surface water (with O2-sensor data) and b) average oxygen/hydrogen sulphide concentrations in bottom water (without sensor data) of the studied Baltic Sea areas of February to November: Belt Sea, Mecklenburg Bight, Arkona Sea, Odra Bight, Bornholm Sea, southern Gotland Sea, central Eastern Gotland Sea, Northern Gotland Sea, and Western Gotland Sea.

The oxygen concentration in surface water of respective areas from the Belt Sea to the western Gotland Sea is basically controlled by the seasonal changing temperature and primary production (Fig. 24a). However, physical processes like mixing and upwelling could intermediately cause a deviating oxygen concentration. The highest average oxygen concentrations measured during the monitoring campaigns were consequently observed in February, March and May between about 350 µmol l^{-1} and 420 µmol l^{-1} oxygen in 2023. Thereby, the maxima in the western Baltic Sea were mostly measured in March, as this month usually shows the lowest water temperature and spring bloom started earlier in these areas. In the Bornholm Sea and the different Gotland Sea areas likely the later spring bloom shifted the maxima to May. After the summer minimum in July between 255 µmol l^{-1} and 300 µmol l^{-1} oxygen in 2023, subsequent cooling and enhanced input of atmospheric oxygen at autumn weather conditions increased the oxygen concentration from 290 µmol l^{-1} to 340 µmol l^{-1} oxygen in November.

The bottom water of the shallow Belt Sea, Mecklenburg Bight and the Arkona Sea (Fig. 24b) showed a similar seasonal pattern as the surface water (Fig. 24a), however at a slightly lower concentration level of 230 µmol l^{-1} to 350 µmol l^{-1} in February, March and May. The lowest regional average oxygen concentrations in bottom water in the western Baltic Sea were 120 µmol l^{-1} and 150 µmol l^{-1} recorded in the Mecklenburg Bight, and the Arkona Sea, respectively in August 2023. Until November, the oxygen concentration improved to 235 µmol l^{-1} and 180 µmol l^{-1}, respectively, for these areas. The sampling schedule with five monitoring cruises annually, is relatively coarse and insufficient to record the annual oxygen minima at the respective sites. Thus, the summer monitoring measurements give only a rough impression of oxygen deficit in summer/early autumn of shallow Baltic Sea water. However, July and August 2023 were better than previous years, as strong wind periods enabled some oxygen supply by deeper mixing. The average oxygen concentration in the bottom water of the Bornholm Sea showed some variability in 2023 between 25 µmol l^{-1} and 100 µmol l^{-1} in the first half of the year caused by inflow activity in late summer and Winter 2022/2023, and weak euxinia of hardly detectable -1 µmol l^{-1} oxygen in August and November. In the south-eastern Gotland Sea an average weak sulfidic situation was measured during February and August in 2023 with -11 µmol l^{-1} oxygen equivalents. However, the passage of oxygen bearing filaments is also apparent in the Fig. 25 and Fig. 26. The situation in the bottom water of the deep basin is different and dominated by euxinic conditions. In the eastern Gotland Sea during the year 2023, the oxygen equivalent concentration of hydrogen sulphide reached record low concentrations between -310 µmol l^{-1} in March and -740 ml l^{-1} in August, in the northern Gotland Sea between -64 µmol l^{-1} and -138 µmol l^{-1}, and in the western Gotland Sea between -92 µmol l^{-1} and -400 µmol l^{-1} oxygen equivalents, respectively. This showed a similar situation as last year for the northern Gotland Sea, but indications of worsening situation in the eastern and western Gotland Basin compared to the last year was also noticeable for the deepest sites. However, a certain seasonal variability is certainly caused by the shallower stations in the sea area and is also biased by changes of the sampling grid for this comparison.

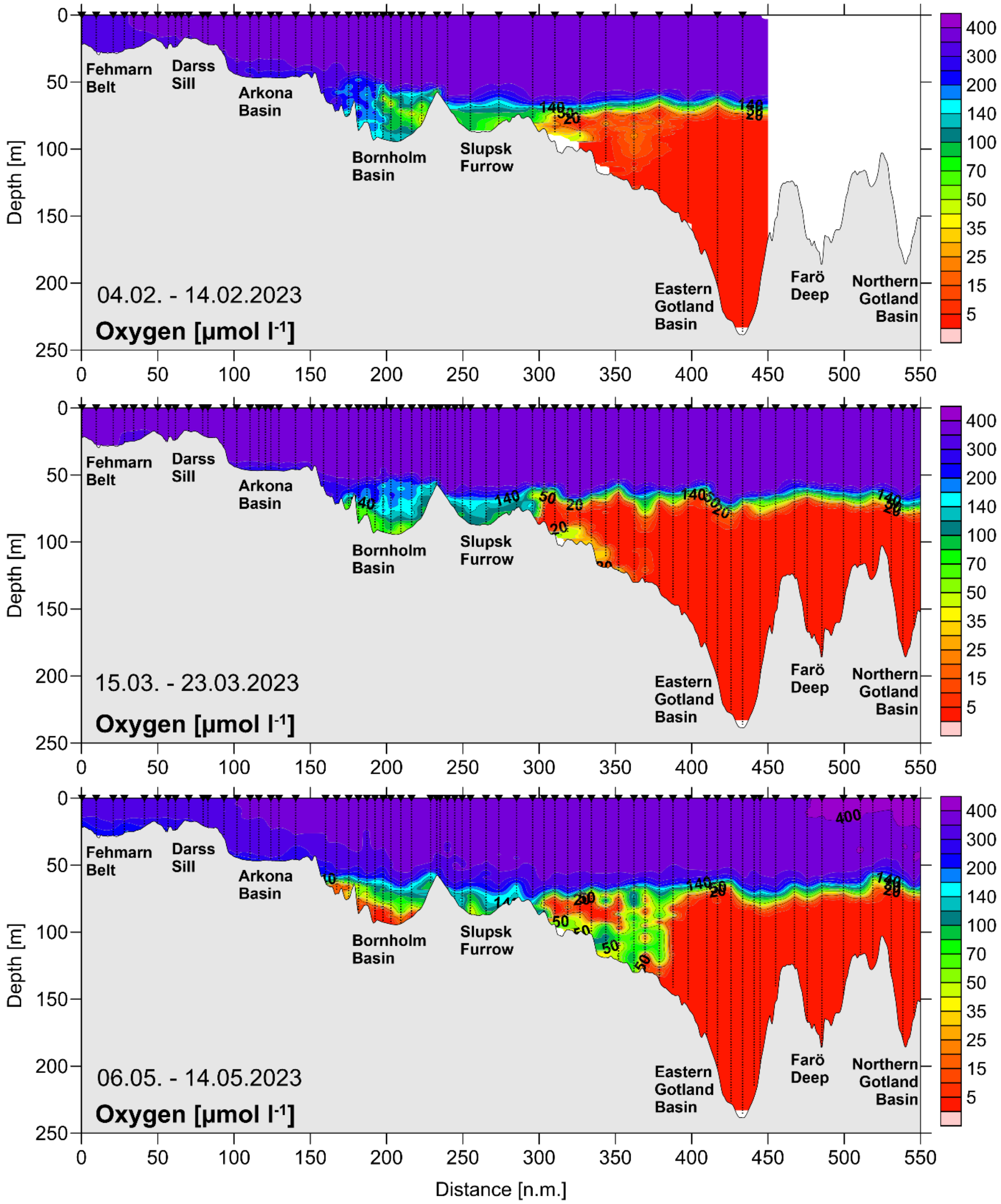


Fig. 25: Vertical distribution of oxygen (without H2S) during the February, March and May cruises in 2023 between the Darss Sill and the northern Gotland Basin. Values below 5 µmol l-1 could not be distinguished from 0 µmol l-1.

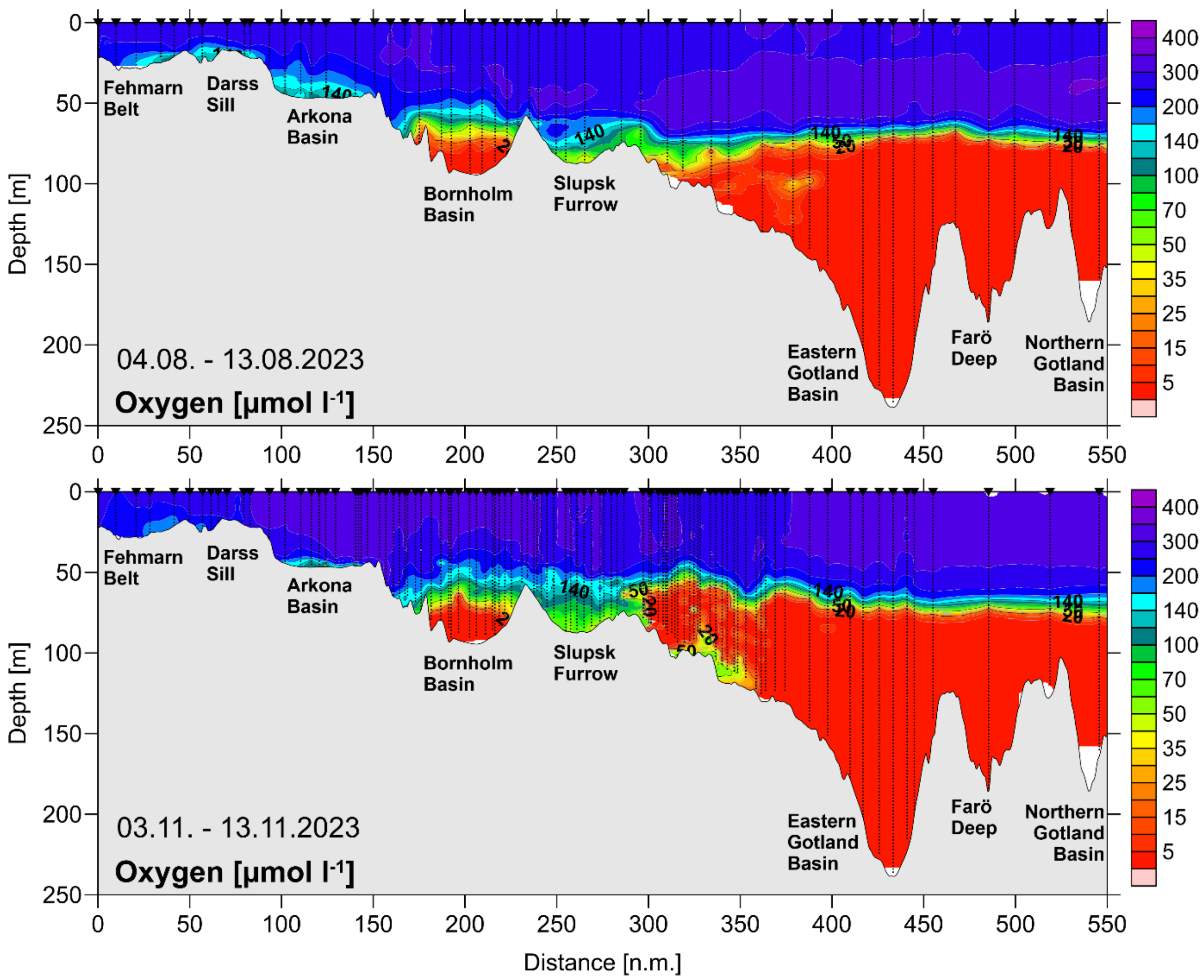


Fig. 26: Vertical distribution of oxygen (without H_2S) during the August and November cruises in 2023 between the Darss Sill and the northern Gotland Basin. Values below 5 µmol l^{-1} could not be distinguished from 0 µmol l^{-1}.

The oxygen condition of the deep water of the central Baltic Sea is primarily influenced by the occurrence or absence of moderate and strong barotropic and/or baroclinic inflows. Some baroclinic inflows and a minor barotropic inflow of late summer/autumn 2022 transported warm oxygenated water to the south-eastern Bornholm Basin and through the Słupsk Furrow until the southern Eastern Gotland Basin (Fig. 25, Fig. 26: Vertical distribution of oxygen; Fig. 18, Fig. 19: Temperature distribution along the Thalweg). The water reflected oxygen concentrations in February 2023 of 55 µmol l^{-1} to 145 µmol l^{-1}. In the south-eastern Bornholm Basin, the water body showed enclosures of less oxygenated water of 40 µmol l^{-1} and increasing oxygen values to its boundary at that time (Fig. 25). It looked as if the former bottom water was folded to the inside of the warm water body on the way uphill. In the Słupsk Furrow the water was almost horizontally layered with highest values at the top of about 160 µmol l^{-1}. But in the southernmost Eastern Gotland Basin still up to 65 µmol l^{-1} were noticeable in the otherwise anoxic and euxinic water below the halocline. In March, cold water from a minor barotropic inflow event of December 2022 entered the Arkona Sea and surpassed and entrained the warm water until the centre of the Bornholm Sea by water with elevated oxygen of 145 µmol l^{-1} to 255 µmol l^{-1}. An isolated parcel of the warm oxygenated water of 30 µmol l^{-1} in the southern Gotland Sea moved further down the Thalweg until a depth of about 120 m. In May 2023, the oxygen was distributed in the southern part of the eastern Gotland Basin from below 60 m down to 130 m, reflecting an oxygen concentration of 60 µmol l^{-1} to 120 µmol l^{-1}. However, some enclosures of water without detectable oxygen were also visible. As well the bottom water of the northern and central Bornholm Sea turned anoxic again. In August the remnants of the inflow were still visible (Fig. 26) in the intermediate water of the Bornholm Sea and the Słupsk Furrow (‹ 120 µmol l^{-1}) and a small water parcel at 100 m depth of about 30 µmol l^{-1} in the water column of the southern Gotland Sea. Until November a new warm water inflow surpassed the Bornholm Sea deep water, ventilated Słupsk Furrow and already elevated the oxygen concentration partly at the slope of the southern Eastern Gotland Basin up to about 65 µmol l^{-1}.

4.4 Nutrients: Inorganic nutrients

The Baltic Sea is still impacted by eutrophication, according to the most recent integrated eutrophication status assessment for 2016–2021 (HELCOM 2023). "Only 12 of the 252 assessment units included in the HELCOM evaluation, which covered both open (19) and coastal water bodies (233), achieved good status. This is further demonstrated by the fact that 93.8 % of the Baltic Sea's surface area, from the Kattegat to the inner bays, is affected by eutrophication."

The recent Holistic Assessment of the Status of the Baltic Sea (HOLAS) (HELCOM 2023) tracks progress towards the achievement of healthy Baltic Sea that is targeted by implementation of the 2021 Baltic Sea Action Plan (HELCOM 2021a) and provides a regional contribution to the reporting under the Marine Strategy Framework Directive (MSFD) (EC 2008). The eutrophication status is evaluated by the criteria groups a) nutrient levels, with the indicators dissolved inorganic nitrogen and phosphorus and total nitrogen and phosphorus, b) direct effects, with the indicators chlorophyll and cyanobacterial bloom index, and c) indirect effects, with the indicators water transparency, oxygen debt, shallow water oxygen, state of the soft-bottom macrofauna community. It is concluded that nitrogen and phosphorus load has decreased, however, it still significantly exceeded agreed limits for nitrogen of 792 kt and for phosphorus of 21.7 kt input. The riverine input of nitrogen (305 kt) and phosphorus (15.8 kt) for the five biggest rivers exceeded the input ceiling by 30 % and by 121 % in 2017, respectively (HELCOM 2021b). The atmospheric inputs of nitrogen oxides and ammonium are modelled to have decreased by 40 % and 8 % since the reference period 1997-2003 (GAUSS & KARLSEN 2022), but were still 111 kt and 99 kt in 2020, respectively. Thereby, Germany contributed about one fifth of the atmospheric nitrogen deposited to the Baltic Sea. The disillusioning result for the Baltic Sea is that all open sea assessment areas failed a good status with negative impacts on organisms and human well-being. Moreover, it is concluded that even when agreed nutrient reduction targets are achieved, the natural conditions of the Baltic Sea do not favour a fast recovery. It may take decades or even centuries to achieve a healthy Baltic Sea. However, it is emphasized that pressures like nutrient inputs should be minimized with increased effort to make the Baltic Sea ecosystem more resilient against increasing effects of climate change (HELCOM 2023).

4.4.1 Surface water processes

The idealized assumption that nitrate and phosphate concentrations in the surface water of temperate latitudes exhibit a typical annual cycle with high concentrations in winter, almost simultaneous depletion (REDFIELD et al. 1963) during spring and summer, and recovery in autumn

(NAUSCH & NEHRING 1996, NEHRING & MATTHÄUS 1991) seems partly no longer valid. Nitrate is still completely taken up early in the year by the spring bloom and is replenished during late autumn and winter, whereas phosphate significantly declines in April/May, but persists at low concentration almost throughout the entire summer. Thus, blooms of diazotrophic cyanobacteria that use dinitrogen gas as nitrogen source for growth are enabled during summer nitrate limitation.

The annual cycle of nitrate and phosphate concentrations in surface water at the stations Gotland Deep and Bornholm Deep was compared to the surface water temperature development in 2023 (Fig. 27). For this purpose, the data of five monitoring cruises of the IOW were combined with data of the Swedish Meteorological and Hydrological Institute (SMHI) to get a better resolution of the seasonal patterns. In the central Baltic Sea, a typical phase of elevated nutrient concentrations usually develops during deep mixing in winter, which lasted two to three months (NAUSCH et al. 2008).

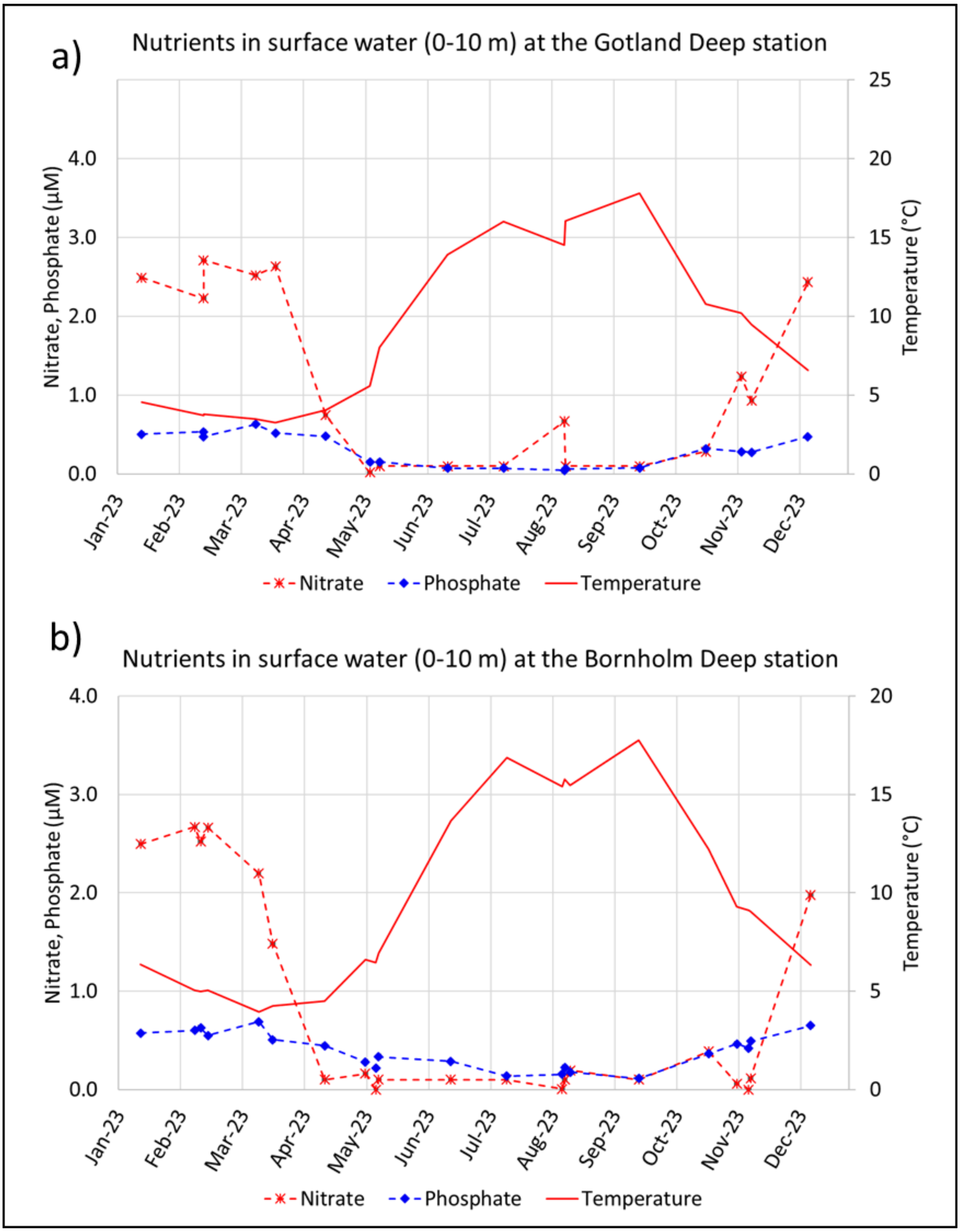


Fig. 27: Seasonal cycle of average phosphate and nitrate concentrations in 2023 compared to the temperature development in the surface layer (0-10 m) at the Gotland Deep station (a) and at the Bornholm Deep station (b), respectively, by depicting IOW and SMHI data.

The relatively low maximum nitrate concentration of about 2.7 µmol l^{-1} in 2023 (3.4 µmol l^{-1} in 2022) at Gotland Deep site as well as about 2.7 µmol l^{-1} (2.9 µmol l^{-1} in 2022) at Bornholm Deep station were measured in January and February. The relative stable value lasted at Gotland Deep site until mid-March and nitrate was found completely consumed early May. At the Bornholm Deep station, the decline of nitrate began in mid-March and nitrate was almost depleted early April. Thereby, the relative low nitrate winter Maximum values could be caused by the relative mild winter temperatures and some consumption early in the year 2023. Increasing nitrate loss in deep water could also contribute to declining surface water winter values in recent years. Whereas phosphate was measured between 0.50 µmol l^{-1} and 0.63 µmol l^{-1} at Gotland Deep site and 0.55 µmol l^{-1} and 0.63 µmol l^{-1} at Bornholm Deep site in Jan/Feb 2023. During summer phosphate was low, but significantly available of about 0.07 µmol l^{-1} at Gotland Deep and higher at Bornholm Deep site of even 0.18 µmol l^{-1} during summer. Nitrate in turn showed a slight recovery after a stormy period early August of 0.7 µmol l^{-1} at Gotland Deep site. Thus, the spring bloom in 2023 likely ended in the Bornholm Sea end of March, and at the Gotland Deep station end of April. A significant replenishment of nitrate in the surface water did not take place at the Bornholm Deep station before mid-November and at Gotland Deep site end of November. At that time, cooling to about 10°C at Bornholm Deep site and 12°C at Gotland Deep site enabled wind induced mixing in autumn weather conditions and a supply of nutrients from deeper layers.

The relative low winter nitrate concentration resulted in a relative low dissolved inorganic nitrogen/phosphorus ratio (DIN/DIP) at Gotland Deep and at Bornholm Deep site present in the winter surface water (Fig. 28). The ideal uptake ratio of about 16 was already shown by an early study of REDFIELD et al. (1963) and was proven to be a valuable approximation many times thereafter. To investigate this in more detail, data assed in surface water in the respective sea area were used for averaging. The DIN/DIP ratio (mol mol^{-1}) was determined from the sum of ammonium, nitrate, and nitrite concentrations versus the phosphate concentration. The surface water DIN/DIP ratio in the Baltic Sea in winter 2022/2023 ranged between 5.0 mol mol^{-1} and 13.9 mol mol^{-1} in the investigated sea areas. Because of a bad weather situation in February, no data of the northern and western Gotland Sea were available. Closest to the Redfield ratio were the data of the Odra Bight with a ratio between 10.9 mol mol^{-1} and 17.9 mol mol^{-1} in the years from 2019 to 2023 (Fig. 28). In the other investigated areas, the N/P ratio showed a decreasing trend from west to east: Belt Sea 9.2 mol mol^{-1}, Mecklenburg Bight 8.7 mol mol^{-1}, Arkona Sea 6.9 mol mol^{-1}, Bornholm Sea 5.5 mol mol^{-1} and south-eastern Gotland Sea 5.0 mol mol^{-1}. Further to the central Eastern Gotland Sea, the ratio increased to 6.2 mol mol^{-1} in 2023. The distribution pattern is however similar to the situation in the last year and confirmed again in 2023 that nitrogen was a limiting factor in the Baltic Proper, giving diazotrophic cyanobacteria an advantage compared to primary producers that depend on nitrate.

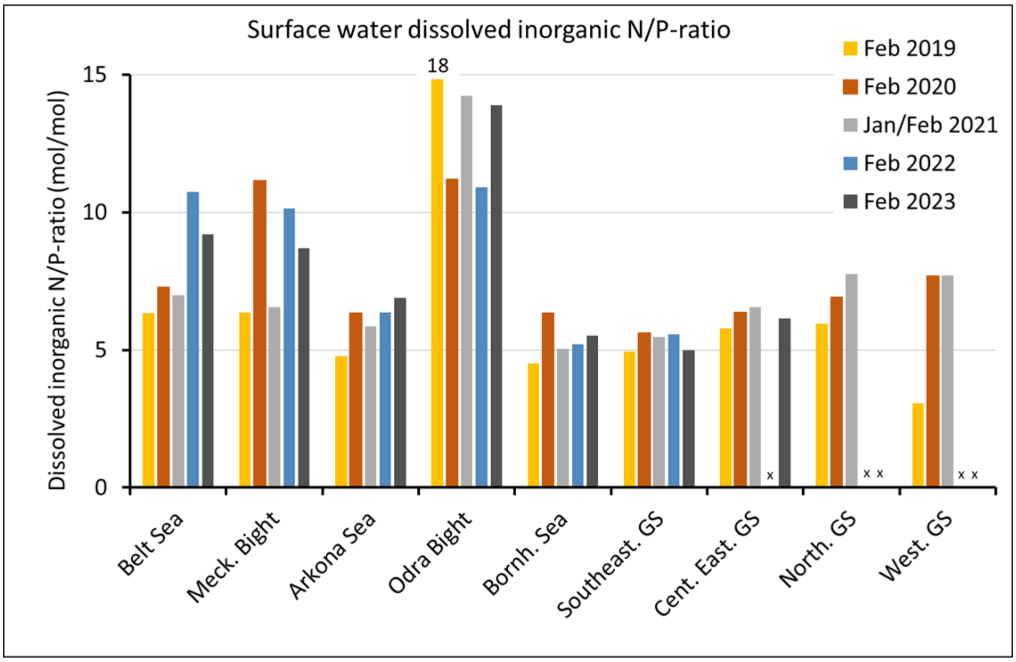


Fig. 28: Average winter dissolved inorganic nitrogen versus phosphate ratio in surface water of selected Baltic Sea areas for 2019 to 2023.

Winter phosphate and nitrate concentrations in surface water were obtained from measurements in February (or late January) of recent years (Table 5). The lowest phosphate winter concentrations since 2019 were measured on the selected stations in the western Baltic Sea, the Bornholm Sea and on the Karlsö Deep site in southern Western Gotland Basin in 2020. The reason could be the extreme mild winter season in 2020 and a diatom dominated spring bloom that started in February (NAUMANN et al. 2021; DUTZ et al. 2022). Whereas on the respective stations in the Eastern Gotland Basin and in the northern Western Gotland Basin a lower phosphate concentration after the mild winter 2022/2023 was measured.

A similar situation was seen in the winter nitrate concentration of surface water. The representative stations of the different Baltic Sea areas showed either in the western Baltic Sea for Fehmarn Belt, Arkona Sea and Karlsö Deep in 2020 the minima, however, nitrate was at the Mecklenburg Bight and Karlsö Deep station even lower in 2019. Bornholm Deep showed equal nitrate concentrations in both years, whereas at the Fårö Deep, the Gotland Deep and the Landsort stations lower concentrations were measured in 2023. An influence of the increasing oxygen debt in the deep Gotland Sea could be contribute to a low winter nitrate value in surface water during winter, as deep mixing in winter could bring up water with partly reduced nitrate concentration. However, decreased atmospheric and riverine input may also contribute to the observation.

Table 5: Mean nutrient concentrations in the surface layer (0-10 m) in winter in the western and central Baltic Sea 2019-2023 (IOW and SMHI data).

Table 5.1: Surface water ***phosphate*** *concentrations (**µmol l-1**) in February (Minima in bold).*

Station	2019	2020	2021	2022	2023
360 (Fehmarn Belt)	0.42 ±0.00	**0.26 ±0.04**	0.90 ±0.03	0.76 ±0.00	0.68 ±0.02
022 (Lübeck Bight)	-	-	0.82 ±0.01	0.72 ±0.00	0.70 ±0.01
012 (Meckl. Bight)	**0.58 ±0.00**	**0.58 ±0.00**	0.83 ±0.01	0.64 ±0.00	0.72 ±0.00
113 (Arkona Sea)	0.59 ±0.00	**0.43 ±0.01**	0.72 ±0.03	0.57 ±0.00	0.52 ±0.01
213 (Bornholm Deep)	0.61 ±0.02	**0.51 ±0.03**	0.81 ±0.02	0.66 ±0.01	0.58 ±0.04
271 (Gotland Deep)	0.68 ±0.02	0.67 ±0.00	0.71 ±0.03	0.71 ±0.00	**0.50 ±0.02**
286 (Fårö Deep)	0.71 ±0.01	0.57 ±0.01	0.64 ±0.01	0.73 ±0.01	**0.55 ±0.01**
284 (Landsort Deep)	0.70 ±0.01	0.59 ±0.00	0.64 ±0.00	0.74 ±0.01	**0.56 ±0.01**
245 (Karlsö Deep)	0.65 ±0.01	**0.58 ±0.01**	0.74 ±0.04	0.69 ±0.01	0.62 ±0.01

Table 5.2: Surface water ***nitrate*** *concentrations (**µmol l-1**) in February (Minima in bold).*

Station	2019	2020	2021	2022	2023
360 (Fehmarn Belt)	1.7 ±0.1	**1.1 ±0.8**	5.0 ±0.5	6.3 ±0.0	5.7 ±0.1
022 (Lübeck Bight)	-	-	**4.3 ±0.2**	5.4 ±0.0	5.3 ±0.1
012 (Meckl. Bight)	**2.8 ±0.1**	3.8 ±0.0	4.5 ±0.1	5.8 ±0.0	5.5 ±0.1
113 (Arkona Sea)	2.6 ±0.0	**2.5 ±0.0**	3.7 ±0.3	2.8 ±0.1	2.8 ±0.1
213 (Bornholm Deep)	**2.6 ±0.1**	2.9 ±0.0	3.8 ±0.1	2.9 ±0.1	**2.6 ±0.0**
271 (Gotland Deep)	4.0 ±0.0	3.4 ±0.1	3.9 ±0.2	3.4 ±0.2	**2.5 ±0.2**
286 (Fårö Deep)	4.0 ±0.0	3.6 ±0.1	4.2 ±0.1	3.5 ±0.0	**2.5 ±0.1**
284 (Landsort Deep)	4.0 ±0.0	3.8 ±0.0	4.8 ±0.0	**2.4 ±0.1**	2.8 ±0.2
245 (Karlsö Deep)	**1.2 ±0.1**	3.6 ±0.1	4.1 ±0.2	2.4 ±0.0	3.0 ±0.0

A statistically solid decadal trend of reduced nutrient concentrations that has already been observed in coastal water is still disturbed by interannual variability of the nutrient concentrations of central Baltic Sea surface water in winter (NAUSCH et al. 2011, NAUSCH et al. 2014). However, a decrease of the nutrients/salinity gradients between coastal and open sea water were shown for many German Baltic Sea areas since 1995, indicating a decline over two decades (KUSS et al. 2020). By comparison with modified nutrient target values elaborated in the TARGEV project (HELCOM 2013), a discrepancy is observed between the phosphate (DIP) and dissolved inorganic nitrogen (DIN), basically nitrate in surface waters, in terms of reaching the targets. The target values of DIN and DIP winter concentrations are for the Kiel Bight 5.45 µmol l^{-1}/0.60 µmol l^{-1}, Mecklenburg Bight 4.24 µmol l^{-1}/0.50 µmol l^{-1}, the Arkona Sea 2.90 µmol l^{-1}/0.36 µmol l^{-1}, for the Bornholm Sea 2.52 µmol l^{-1}/0.32 µmol l^{-1}, and for the eastern Gotland basin 2.59 µmol l^{-1}/0.29 µmol l^{-1}, respectively. This indicates that in contrast to phosphate the nitrate winter concentration (ammonium and nitrite reflect minor contributions) may reach the respective target values in certain years, but a permanent fulfilment appears unlikely in the near future. Moreover, the deep water of central basins constitutes a strong nitrate sink, because of the current intense euxenia. Thus a certain nitrate decline may not indicate the input reductions alone. For phosphate very likely it may need some more decades to reach the targets that were aimed.

4.4.2 Deep water processes in 2023

In central Baltic Sea deep water, the distribution of nitrate, phosphate and ammonium is primarily influenced by the occurrence or absence of strong barotropic and/or baroclinic inflows and, thus, by its oxygen/hydrogen sulphide concentrations in deep water. Since the short recovery after the MBI 2014/2015, the accumulation of ammonium and phosphate in the deep water of the central basins had even continued on a high concentration level in 2023, or were almost on the same high concentration level in recent years. Nitrate was mostly not detected in deep water. In the reference depth of Gotland Deep´s deep water, the increase of the phosphate concentration was from 6.1 µmol l^{-1} in 2022 to 6.2 µmol l^{-1} in 2023. Similarly, for the Karlsö Deep, where phosphate was slightly higher, from 4.2 µmol l^{-1} to 4.3 µmol l^{-1} in 2023. Fårö Deep and Landsort Deep showed almost the same phosphate concentration in 2023 compared to 2022, 4.7 µmol l^{-1} and 4.1 µmol l^{-1}, respectively (Table 6). The Bornholm Deep was frequently receiving oxygenated water from the Arkona Basin that intermittently changed the oxygen/hydrogen sulphide status of deep water in recent years. This caused strong intra annual and inter annual variability of nutrient concentrations. For example, during locally oxic water conditions, phosphate could be bound to iron/manganese particles that subsequently sink to the sediment. During anoxia, the particles are dissolved and then phosphate is released back to the water column. The annual mean phosphate concentration changed in recent years between 2.9 ± 1.0 µmol l^{-1} (2020) and 5.2 ± 4.0 µmol l^{-1} (2022) in the Bornholm Deep since 2019.

The fading of the MBI impact (NAUMANN et al. 2018) is also reflected in the depletion of nitrate to the detection limit in deep water. Only the Bornholm Deep showed elevated nitrate concentrations with strong intra annual variability under sporadic oxic conditions in recent years, between 4.1 µmol l^{-1} in 2022 and 6.4 µmol l^{-1} in 2023. Since on Gotland Deep, Fårö Deep, Landsort Deep and Karlsö Deep stations no significant amounts of nitrate were detected since 2019 (Table 6) in the respective deep water reference depths, dissolved inorganic nitrogen is present as ammonium. An explanation is that anoxic conditions prevent mineralization of organic matter to nitrate and instead, ammonium is formed. Therefore, basically ongoing accumulation of ammonium in deep water was recorded in Baltic Sea deep water, in the Gotland Deep from 27.9 µmol l^{-1} in 2022 to even 35.4 µmol l^{-1} in 2023. On Fårö Deep station, ammonium increased from 15.9 µmol l^{-1} in 2022 to 16.9 µmol l^{-1}, at Landsort Deep site still from 12.6 to 12.8 µmol l^{-1} and on Karlsö Deep a similar ammonium concentration was determined in 2022 16.0 as in 2023 of 15.9. In the Bornholm Deep the annual mean ammonium concentration in 80 m reference depth changed from 3.2 ± 6.6 µmol l^{-1} in 2022 to 1.1 ±.3.1 µmol l^{-1} in 2023 indicating a dominating oxic situation in 2023 with strong changes in recent years (Table 6).

Table 6: Annual means and standard deviations for phosphate (Table 6.1), nitrate (Table 6.2) and ammonium (Table 6.3) in the deep water of the central Baltic Sea (IOW and SMHI data).

*Table 6.1: Annual mean deep water **phosphate** concentration (µmol l^{-1}; Maxima in bold).*

Station	depth m	2019	2020	2021	2022	2023
213 (Bornholm Deep)	80	3.78 ±1.40	2.88 ±1.03	4.49 ±2.65	**5.15 ±4.02**	2.59 ±1.57
271 (Gotland Deep)	200	4.38 ±0.25	5.14 ±0.34	5.39 ±0.16	6.14 ±1.03	**6.18 ±0.27**
286 (Fårö Deep)	150	4.02 ±0.45	3.36 ±0.42	4.37 ±0.17	4.66 ±0.32	**4.68 ±0.53**
284 (Landsort Deep)	400	3.64 ±0.57	3.98 ±0.24	3.69 ±0.14	4.06 ±0.21	**4.11 ±0.56**
245 (Karlsö Deep)	100	3.51 ±0.29	3.89 ±0.25	3.98 ±0.32	4.17 ±0.29	**4.33 ±0.31**

*Table 6.2: Annual mean deep-water **nitrate** concentration (µmol l^{-1}; Minima in bold), values below detection limit are indicated by ‹ 0.2.*

Station	depth m	2019	2020	2021	2022	2023
213 (Bornholm Deep)	80	6.8 ±2.9	7.7 ±4.1	**2.9 ±4.5**	4.1 ±5.0	6.4 ±5.0
271 (Gotland Deep)	200	**‹ 0.2**	**‹ 0.2**	**‹ 0.2**	0.2 ±0.4	**‹ 0.2**
286 (Fårö Deep)	150	**‹ 0.2**	0.3 ±0.6	**‹ 0.2**	0.2 ±0.4	**‹ 0.2**
284 (Landsort Deep)	400	**‹ 0.2**	**‹ 0.2**	**‹ 0.2**	**‹ 0.2**	**‹ 0.2**
245 (Karlsö Deep)	100	**‹ 0.2**	**‹ 0.2**	**‹ 0.2**	**‹ 0.2**	**‹ 0.2**

*Table 6.3: Annual mean deep-water **ammonium** concentration (µmol l^{-1}; Maxima in bold).*

Station	depth m	2019	2020	2021	2022	2023
213 (Bornholm Deep)	80	1.5 ±3.1	0.4 ±0.7	**4.0 ±4.9**	3.2 ±6.6	1.1 ±3.1
271 (Gotland Deep)	200	12.2 ±3.8	20.1 ±5.0	22.8 ±0.9	27.9 ±7.5	**35.4 ±19.5**
286 (Fårö Deep)	150	9.1 ±1.2	7.3 ±3.6	12.2 ±1.6	15.9 ±3.0	**16.9 ±3.8**
284 (Landsort Deep)	400	8.0 ±1.0	9.4 ±2.2	10.3 ±0.3	12.6 ±1.5	**12.8 ±2.5**
245 (Karlsö Deep)	100	9.4 ±5.1	12.8 ±2.9	12.1 ±3.8	**16.0 ±3.9**	15.9 ±3.0

Fig. 29 illustrates the phosphate and nitrate concentration distributions in the water column on the Thalweg transect between the Mecklenburg Bight and the western Gotland Sea in February, March, May, August and November 2023 (small maps within the panels of Fig. 29 indicate the available data on the respective cruise). Thereby, point measurements at their respective depth (grey dots) were enlarged on the basis of weighted-average gridding to give an impression of spatial nutrient concentration distributions of phosphate and nitrate along the thalweg transect. The large areas of purple shading correspond to relatively low concentrations of below 0.2 µmol l^{-1} phosphate and 1 µmol l^{-1} nitrate. Red and pale red shadings correspond to phosphate concentrations up to a maximum of 8 µmol l^{-1} and for nitrate up to 12 µmol l^{-1} (Fig. 29).

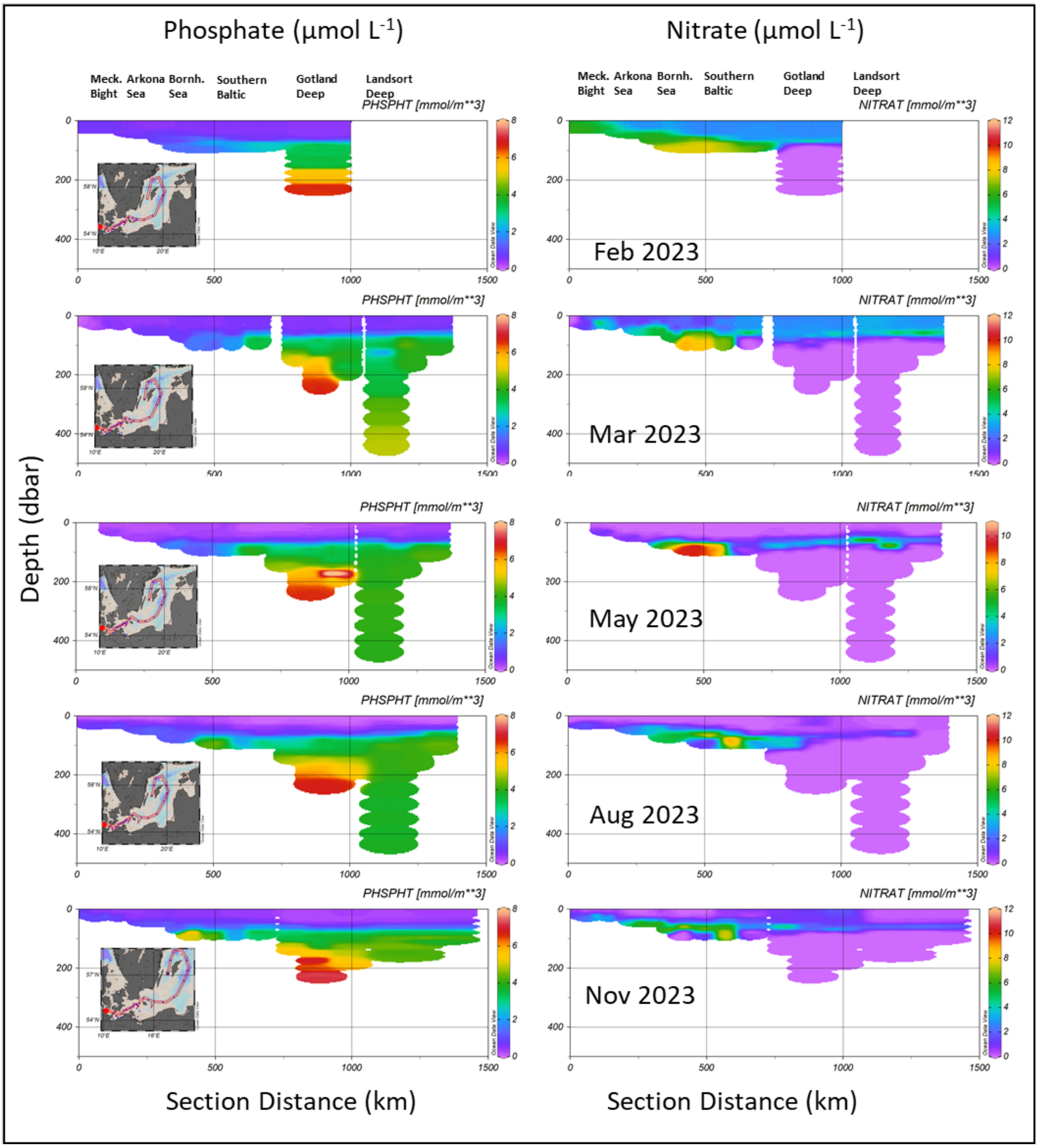


Fig. 29: Vertical distribution of phosphate (left column) and nitrate (right column) in 2023 between the Mecklenburg Bight and the western Gotland Basin measured on the IOW monitoring cruises in February, March, May, August and November; in Feb, the northern and western Gotland Sea and in Nov the Landsort Deep site could not be sampled (SCHLITZER 2018).

During the **February** campaign, the surface mixed layer of changing violet shading reflected a weak phosphate concentration gradient of 0.7 µmol l^{-1} in the Mecklenburg Bight and 0.5 µmol l^{-1} to 0.6 µmol l^{-1} in the Arkona Sea and further to the central Eastern Gotland Basin. A phosphate maximum of 2.3 µmol l^{-1} at about 10 m above the sea floor is visible in the Bornholm Sea as a light blue ribbon. The elevated phosphate concentration above the bottom water increased to 2.6 µmol l^{-1} in the southern Baltic Sea. At Gotland deep station the concentration increased from 3.6 µmol l^{-1} in 80 m to 6.7 µmol l^{-1} in bottom water. The nitrate concentration in surface water decreased from 5.5 µmol l^{-1} in the Mecklenburg Bight to below 3 µmol l^{-1} in the Arkona Basin, the southern Baltic and the central Eastern Gotland Basin. Relatively high nitrate concentrations were determined in the deep water of the Bornholm Basin and the southern Baltic Sea of about 8 µmol l^{-1}. The green ribbon of 5 µmol l^{-1} to 7 µmol l^{-1} nitrate stretched from the Mecklenburg Bight in the upper 30 m to the southern end of the Eastern Gotland Basin in 90 m to 100 m. At Gotland Deep site, no nitrate was detected below the halocline. In **March**, phosphate was mostly consumed in the Mecklenburg Bight and partly declined in the Arkona Sea and Bornholm Sea surface water, but was still in the range of winter surface water in the central basins. The Gotland Deep bottom water depicted about 7 µmol l^{-1} (red shading) and the deep water above about 6 µmol l^{-1} phosphate (yellow shading) elucidate the strong accumulation of phosphate in this basin. Elsewhere in the deep water, a phosphate concentration of 4.0 µmol l^{-1} to 4.5 µmol l^{-1} was usually measured, but reaching 4.9 µmol l^{-1} phosphate in bottom water of the Landsort Deep, represented by the greenish colour. In 125 m depth at Landsort Deep site, only about 2 µmol l^{-1} phosphate was determined. The concentration distribution of nitrate reflected consumption in the western Baltic Sea surface water. The measured range was from the detection limit in the Mecklenburg Bight to between 1 µmol l^{-1} and 2 µmol l^{-1} in the Arkona and Bornholm Seas, whereas in the Gotland Sea surface water still around 3 µmol l^{-1} of nitrate was present. The oxic Bornholm Sea at that time showed a maximum nitrate concentration of 9 µmol l^{-1} in deep water, and 6 µmol l^{-1} to 7 µmol l^{-1} in intermediate water at 60 m depth. In the Gotland Sea, no nitrate was detected below the halocline. In **May**, surface water showed a low phosphate concentration in the range of 0.05 µmol l^{-1} to 0.20 µmol l^{-1} until 40 m depth. The supply of oxygenated water reduced phosphate concentration in the Bornholm Sea deep water to below 2 µmol l^{-1} and in the Słupsk Furrow to about 2.0 µmol l^{-1}. In the Gotland Deep and Fårö Deep bottom water, 6.7 µmol l^{-1} and 9.2 µmol l^{-1} phosphate, respectively, were determined. In intermediate water and down into the Landsort Deep the phosphate concentration was about 4 µmol l^{-1} indicated by a greenish shading. Nitrate was depleted to below the detection limit in surface water and in the deep Gotland Sea below the halocline. The oxygenated Bornholm Sea showed a maximum nitrate concentration of 10.2 µmol l^{-1}. In **August** surface water phosphate still scattered around 0.05 µmol l^{-1}. In deep water the strong accumulation of phosphate was obvious. In the Gotland Deep the bottom water concentration of 6.8 µmol l^{-1} reflected the maximum concentration. The Eastern Gotland Basin deep water concentration ranged between 6 µmol l^{-1} and 7 µmol l^{-1}, and intermediate water and deep water in the Eastern Gotland Basin and in the whole Landsort Deep were between about 3 µmol l^{-1} and 5 µmol l^{-1}. The nitrate concentration had declined in August in most water bodies of the Thalweg transect to below the detection limit. Only in the deep water of the Bornholm Sea and the Southern Baltic Sea concentrations above 3 µmol l^{-1} nitrate were measured. The maximum was determined in the Słupsk Furrow between the Bornholm Basin and the southern Gotland Sea of more than 9 µmol l^{-1} nitrate close to the seafloor. In **November**, the consumption of nitrate and phosphate concentrations during the months before were partly replenished in surface water. In deep water of the Bornholm Sea 5.6 µmol l^{-1} and in the Gotland Deep even a maximum of 7.3 µmol l^{-1} phosphate were determined. From the deep water until the halocline, the phosphate concentration decreased to about 3 µmol l^{-1}. A phosphate concentration of 3 µmol l^{-1} to 4.5 µmol l^{-1} was also measured in deep water of the western Gotland Basin. In contrast, the nitrate concentration in deep water was still low and depleted to the detection limit of 0.2 µmol l^{-1} nitrate in the Bornholm Sea at anoxic conditions. In the Słupsk Furrow the highest nitrate concentration of 7.7 µmol l^{-1} was determined at that time. A greenish shaded ribbon of about 6 µmol l^{-1} nitrate stretched from the 60 m horizon in the Słupsk Furrow to the Arkona Sea bottom water. In the opposite direction to the western Gotland Basin, a blue ribbon of elevated nitrate concentration of 4.5 µmol l^{-1} to 2.0 µmol l^{-1} reached the Karlsö Deep station at that depth level.

4.5 Nutrients: Particulate organic carbon and nitrogen (POC, PON) in 2023

Particulate organic matter (POM) includes biomass from living microbial cells, detrital material including dead cells, fecal pellets, other aggregated material, and terrestrially-derived organic matter (KHARBUSH et al. 2020). In the photic surface waters of the Baltic Sea, particulate organic carbon (POC) and nitrogen (PON) concentrations are mainly controlled by the presence, growth, and degradation of biologically produced material (SZYMCZYCHA et al. 2017, WINOGRADOW et al. 2019). Although terrestrial inputs are a major source of organic matter to the Baltic Sea regarding the dissolved fraction (NAUSCH et al. 2008, SEIDEL et al. 2017), the significant but weak correlation of POC and salinity as a tracer of mixing fresh- and saline water (data since 1995, all water depths; Pearson's $r=0.06$, $p<0.001$, $n=3013$) indicates that terrigenous POM plays a negligible role at the stations included in this report (TF0012, TF0360, TFO5, TF0109, TF0113, TF0213).

In 2023, POC and PON concentrations were elevated in the surface water of the Baltic Sea at stations TF0109, TF0113 and TF0213 in Arkona and Bornholm Basins in July, indicative of primary production during summer phytoplankton blooms. Exceptionally high POC and PON concentrations were found at TF0360 in March with highest concentrations near the bottom. Depleted inorganic nutrients detected at the same time hint, together with high chlorophyll a fluorescence detected in the patches of high salinity water at this station, towards a phytoplankton source, but resuspension from sedimentary organic matter cannot be ruled out. Generally, POC and PON concentrations were highly correlated (1995 to 2023, Pearson's $r=0.93$, $p<0.001$, $n=3179$), indicating common production and transport pathways. Particulate C/N ratios were low and significantly different from long term means in 2023, while also POC concentrations in the surface waters laid below the long term mean (Table 7). Overall low C/N ratios, below the ratio of living plankton of 6.6 (REDFIELD 1934) may indicate a combined effect of low terrigenous inputs of often higher C/N ratio, and enhanced N-rich material from in-situ production (ZIMMERMAN et al. 2014).

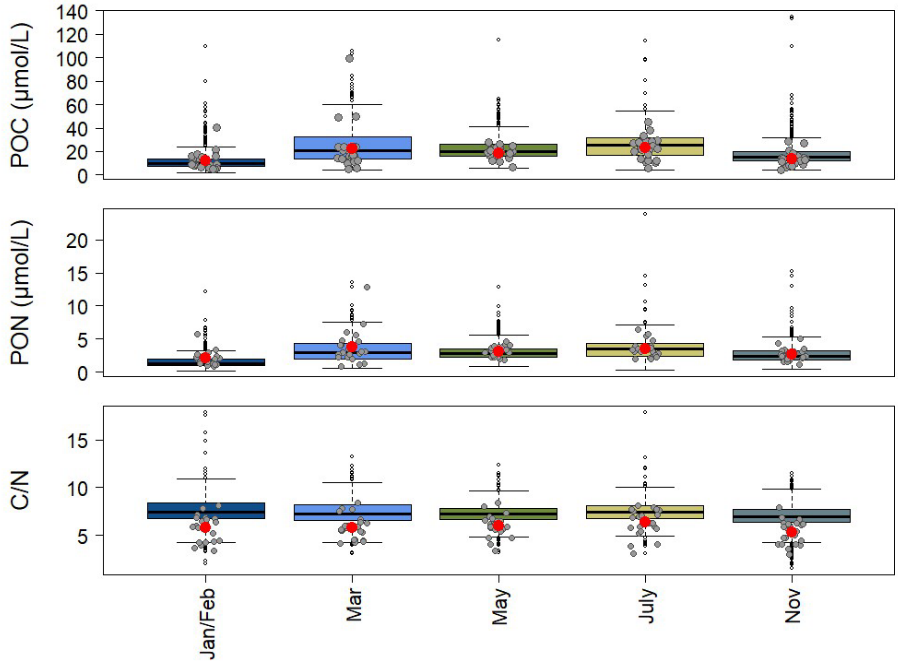


Fig. 30: Boxplots show POC and PON concentrations as well as particulate C/N ratios over the whole water column from 1995 to 2022 by month, with minimum, first quartile, median, third quartile, maximum, and outliers (open circles). Boxplots are overlaid by all 2023 values (gray circles) and means (red circles).

Table 7: Average concentrations and C/N ratio of POC and PON in the surface and deep waters in 2023 in comparison to historic data (1995-2022). Differences in means were analyzed via Welch test, significance and degrees of freedom (df) are provided, significant differences are highlighted in bold. Surface data include samples above 10 m water depth, deep data include deepest water depth sampled per station.

	Surface POM			Deep POM		
	2023	before 2023	Welch-Test	2023	before 2023	Welch-Test
POC (µmol l-1)	**19.9±9.7**	**24.6±14.5**	**p=<0.05, df=33.7**	19.3±16.8	19.5±12.8	p=0.93, df=30.3
PON (µmol l-1)	3.3±1.2	3.3±1.7	p=0.84, df=33.2	3.1±2.1	2.6±1.7	p=0.21, df=30.5
C/N	**5.9±1.3**	**7.4±1.4**	**p<0.001, df=31.3**	**6.1±1.5**	**7.7±1.4**	**p<0.001, df=30.1**

4.6 Organic hazardous substances in surface water of the Baltic Sea in February 2023

The Baltic Sea is largely affected through contamination since the onset of the industrialization in the late 19th century. Riverine transport and atmospheric deposition are the main transport pathways of organic hazardous substances from land based sources in the catchment area into the Baltic Sea (HELCOM 2018).

In this report, obtained data for organic contaminants in Baltic Sea surface water from the February monitoring cruise are summarized (for an overview see Fig. 31) and time series data for the Mecklenburg Bight, Arkona Sea and the Pomeranian Bight are continued. The results are assessed based on criteria of HELCOM as well as the Marine Strategy Framework Directive (MSFD) and the Water Framework Directive (WFD).

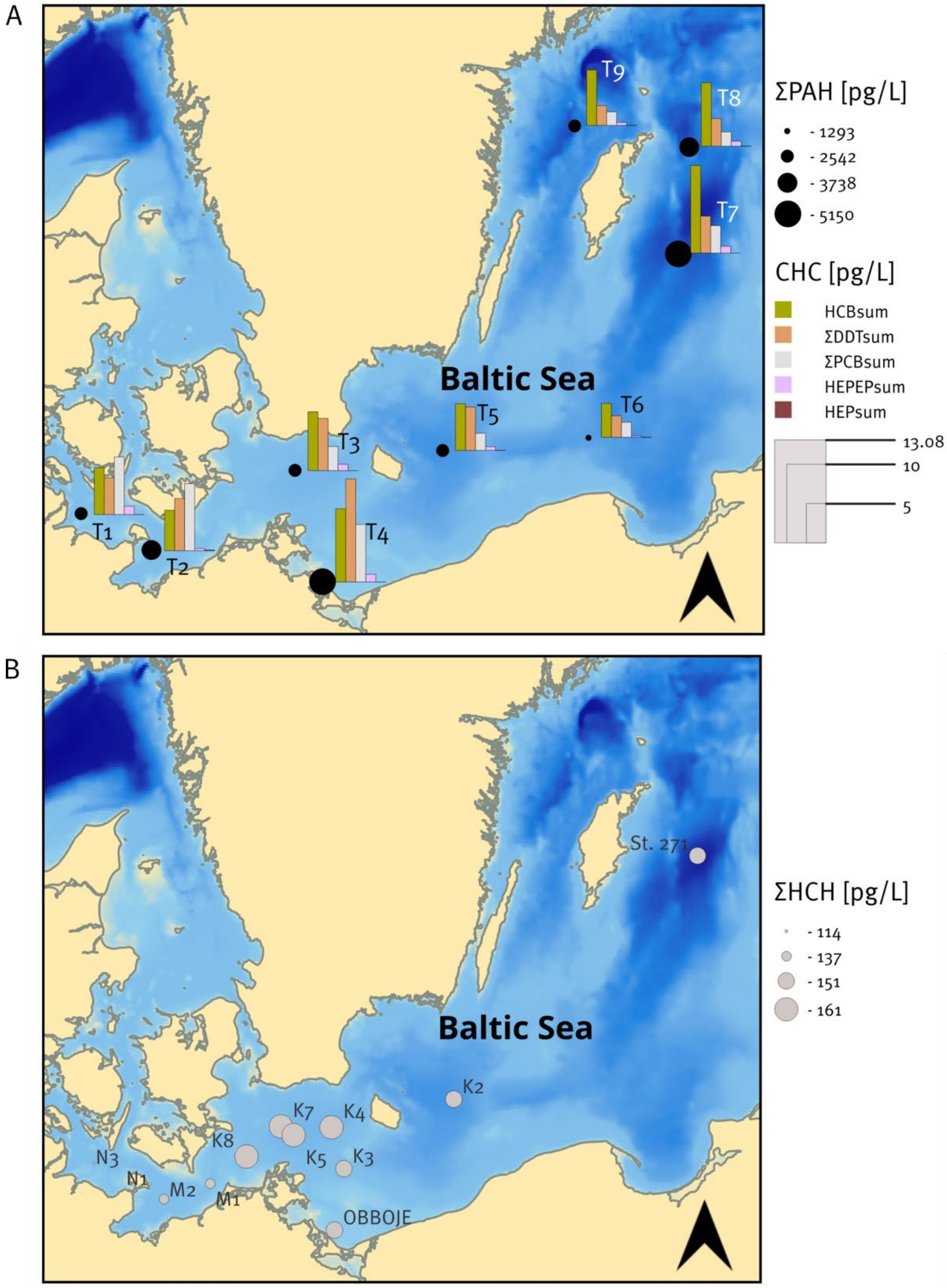


*Fig. 31: **A** Summary of obtained data for PAH and CHC for the Baltic Sea study areas in surface water in Feb 2023. ΣPAH: summarized concentrations of U.S. EPA-PAH (without naph), HCBsum, HEPEPsum, HEPsum,: summarized concentrations for HCB, HEPEP and HEP of dissolved and particulate water fraction, ΣDDTsum: summarized concentrations of DDT and metabolites of dissolved and particulate water fraction, ΣPCBsum: summarized concentrations of PCB_{ICES} congeners of dissolved and particulate water fraction, **B**: Obtained data for HCH in surface water. ΣHCH: summarized concentrations of the HCH isomers α, ß and γ in the whole water sample. (see Table 8 for abbreviations of the contaminants and contaminant groups)*

Samples were taken during winter season at which the Baltic Sea water is most unaffected by biological conditions. Samples were acquired during the expedition EMB311 with RV "Elisabeth Mann Borgese" in February 2023 at sites in the Kiel Bight/Fehmarn Belt (T1), Mecklenburg Bight

(T2), Arkona Sea (T3), Pomeranian Bight (T4), Bornholm Sea (T5), central Baltic Sea (T6), the eastern Gotland Sea (south and north, T7 and T8) and the western Gotland Sea (T9). The surface seawater samples were obtained through transect sampling as shown in Fig. 32. During the transect route a pump/filtration system was used to continuously pump surface water from 5 m below the surface through a GF/F filter and subsequently through an XAD-2 resin packed column with a flow rate of about 1.1 l min^{-1} for 4 to 6 hours.

To observe trends in HCH concentrations in Baltic surface seawater, samples were collected at selected stations along the surface transects (Fig. 32). Sampling was conducted using a 10 l spherical glass sampler from 5 m below sea surface.

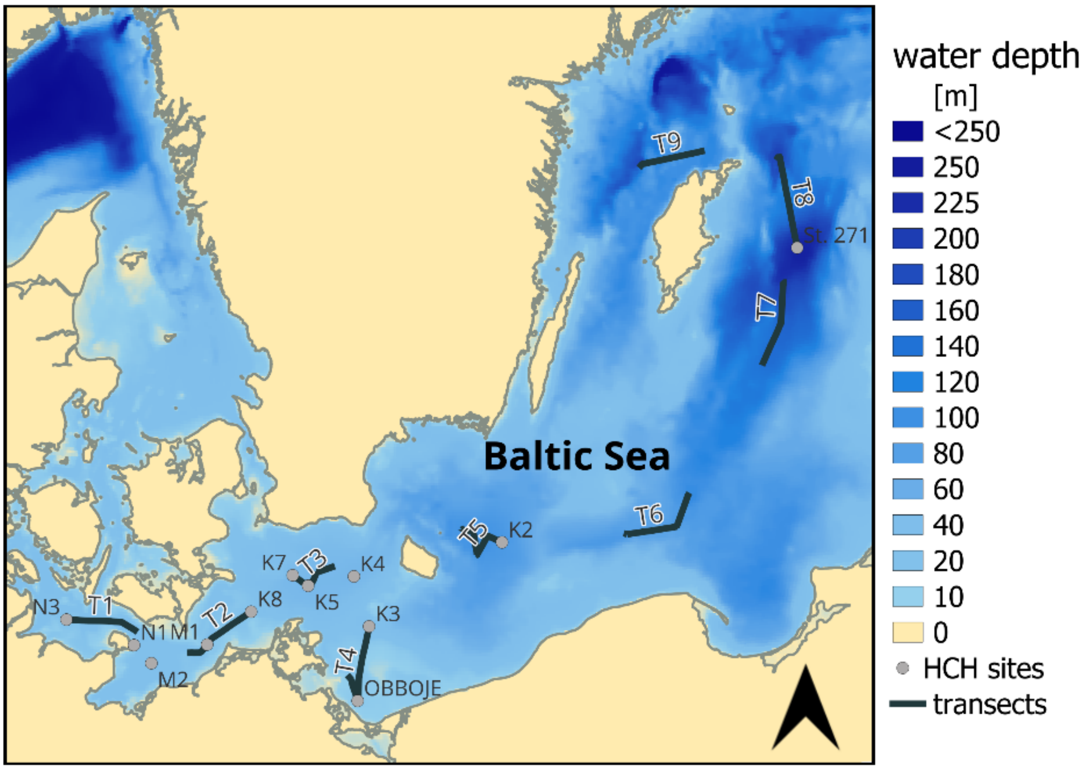


Fig. 32: Surface water sampling transect routes and HCH sampling sites during the February 2023 monitoring. T1: Kiel Bight/Fehmarn Belt, T2: Mecklenburg Bight, T3: Arkona Sea, T4: Pomeranian Bight, T5: Bornholm Sea, T6: central Baltic Sea, T7: east. Gotland Sea (south), T8: east. Gotland Sea, T9 western Gotland Sea.

The samples were analyzed for chlorinated hydrocarbons (CHC) and polycyclic aromatic hydrocarbons (PAH) (Table 8). Chemical analysis of the CHC and PAH in the dissolved and particulate water fractions was conducted as described before (KANWISCHER et al. 2020; SCHULZ-BULL et al. 2011). Analysis of HCH isomers was conducted as described before (ABRAHAM et al. 2017; DANNENBERGER & LERZ 1995; GAUL & ZIEBARTH 1983).

Table 8: Analyzed compounds in Baltic Sea surface water during the February 2023 observation.

Group	Determined substances	Description of the substances/compound groups
Chlorinated hydrocarbons (CHC)	hexachlorocyclohexane (HCH): isomers α, β, γ	HCH has been produced as a technical mixture of 3 isomers (60-70 % α-HCH, 10-15 % β-HCH, 12-15 % γ-HCH) since World War II with the isomer γ-HCH (lindane) as the most effective one.
	ICES-polychlorinated biphenyls (PCB_{ICES}): PCB28/31, PCB52, PCB101, PCB118, PCB153, PCB138, PCB180	Since the 1930s PCBs had been widely used industrially. Commercial PCB formulations consisted of a wide range of PCB congeners differing in number and position of substituted chlorine on the biphenyl rings. The International Council of the Exploration of the Sea (ICES) suggested 7 PCB congeners as indicators for environmental monitoring (PCB_{ICES}).
	dichlorodiphenyltrichloroethane (DDT): *p,p'*-DDT, *o,p'*-DDT dichlorodiphenyldichloroethylene (DDE): *p,p'*-DDE (met.) dichlorodiphenyldichloroethane (DDD): *p,p'*-DDD (met.)	The insecticide DDT has been used as a contact and feeding poison in agriculture and forestry since the 1940s. DDT technical formulations were mixtures of *o,p'* and *p,p'* congeners with *p,p'*-DDT as the predominant one. In the environment DDT degrades to the stable metabolites DDE and DDD.
	hexachlorobenzene (HCB)	HCB is a fungicide which was mainly used for seed treatment and as wood preservative.
	heptachlor (HEP) heptachlor epoxide (cis-heptachlor-exo-epoxide, isomer B) (HEPEP)	The insecticide HEP has been used in agriculture, for wood protection and also for household insect control since 1945. It rapidly converts to mainly HEPEP which is more toxic, bioaccumulative and persistent than the parent compound (EFSA 2007). The cis-isomer of HEPEP is the main metabolite of abiotic and biotic oxidation of HEP (MÜLLER et al. 1997).
	Production and use of DDT, HCB, PCBs, HEP and the HCH isomers is internationally restricted or banned by the Stockholm Convention.	

Polycyclic aromatic hydrocarbons (PAH)	U.S. EPA PAH indicator compounds except naphthalene: acenaphthylene (ACNLE), acenaphthene (ACNE), fluorene (FLE), phenanthrene (PA), anthracene (ANT), fluoranthene (FLU), pyrene (PYR), benzo(*a*)anthracene (BAA), chrysene (CHR), benzo(*b*)fluoranthene (BBF), benzo(*k*)fluoranthene (BKF), benzo(*a*)pyrene (BAP), indeno(1,2,3-*cd*)pyrene (ICDP), dibenzo(*a,h*)anthracene (DBAHA), benzo(*g,h,i*)perylene (BGHIP)	PAHs result from incomplete combustion of organic material. They largely derive from industrial combustion processes such as from fossil fuel or wood combustion. Thus, the presence of these pollutants in the environment is strongly associated to anthropogenic activities. PAHs are persistent in the environment and have toxic, carcinogenic as well as reprotoxic properties. The 16 U.S. EPA PAH indicator compounds serve as representatives for PAH contamination in the environment (KEITH 2015).

4.6.1 Chlorinated hydrocarbons in Baltic Sea surface water

Results for isomers of HCH

Obtained ΣHCH[1] concentrations ranged from about 108 pg l^{-1} at Kiel Bight (N3) to 161 pg l^{-1} in the Arkona Basin (K7) (Fig. 31B, Fig. 33, Appendix 1). Among the analyzed isomers, β-HCH is the predominant one with a share ranging from 50 – 64 %. Slightly increasing concentrations can be observed from Kiel Bight towards the Arkona Sea and the central Baltic Sea which is mainly attributed to increasing concentrations of β-HCH.

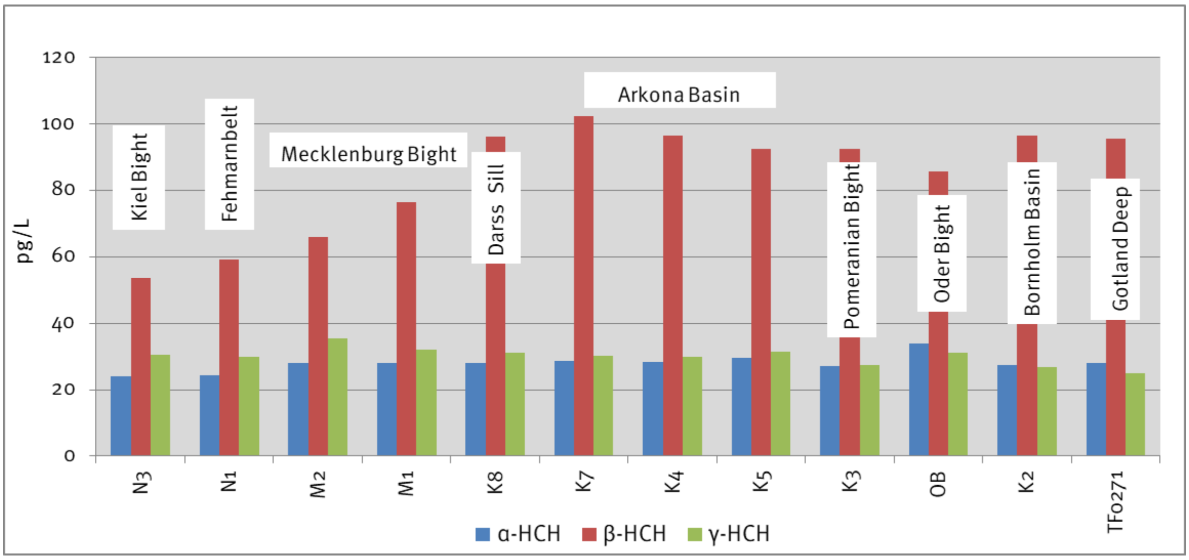


Fig. 33: Concentrations of the HCH isomers in Baltic Sea surface water samples from the February 2023 observation.

ΣHCH concentrations of past observations back to the year 1975 are shown for station K4 in the Arkona Sea (Fig. 34). The long-term data show that concentrations for HCH continuously decrease and that there are no recent inputs.

[1] ΣHCH: summarized concentration of HCH isomers (α, β, γ) in the whole water sample

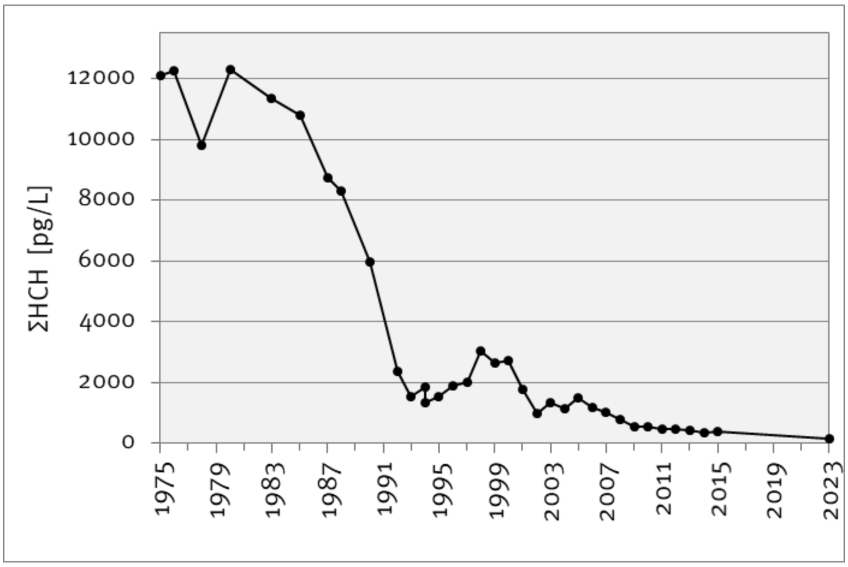


Fig. 34: Time series of concentrations of ΣHCH[1] in Baltic Sea surface water at station K4 in the Arkona Sea in the period from 1975 to 2023 (in the period from 2016 to 2022 sampling was not conducted).

Results for DDT and metabolites

Observed winter concentrations for DDT and its metabolites (ΣDDT_{sum}[2)]) ranged from about 2.53 pg l^{-1} (T9, western Gotland Sea) to 13.08 pg l^{-1} (T4, Pomeranian Bight) (Fig. 35, Appendix 2). Higher concentrations of the long-lived degradation products *p,p'*-DDE and *p,p'*-DDD as compared to *p,p'*-DDT were observed. This implies no recent fresh inputs of DDT which is also reflected by *p,p'*-DDT/*p,p'*-DDE ratios below 0.5 (STRANDBERG et al., 1998) (Table 9).

Table 9: Ratios of p,p'-DDT/p,p'-DDE for the determined concentrations of DDT and metabolites in Baltic Sea surface water. [a] ratios were determined from summarized particulate and dissolved concentrations.

	T1	T2	T3	T4	T5	T6	T7	T8	T9
***p,p'*-DDT/*p,p'*-DDE** [a]	0.19	0.34	0.41	0.22	0.38	0.32	0.41	0.36	0.34

Highest concentration of ΣDDT_{part}[3] of 7.56 pg l^{-1} was obtained for the Pomeranian Bight for which a high suspended matter (SPM) content was found, too. However, the high SPM concentrations at Kiel Bight/Fehmarn Belt and the Mecklenburg Bight is not reflected in the ΣDDT_{part} concentrations at these sites which is different for the concentrations of PCB.

The highest observed concentrations of ΣDDT_{part} and ΣDDT_{diss}[4] for the Pomeranian Bight (T4) indicate a high pressure of this contamination derived from the riverine inflow by the river Odra.

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[2] ΣDDT_{sum}: summarized concentration of DDT congeners and metabolites in particulate and dissolved water fraction

[3] ΣDDT_{part}: summarized concentration of DDT congeners and metabolites in the particulate water fraction

[4] ΣDDT_{diss}: summarized concentration of DDT congeners and metabolites in the dissolved water fraction

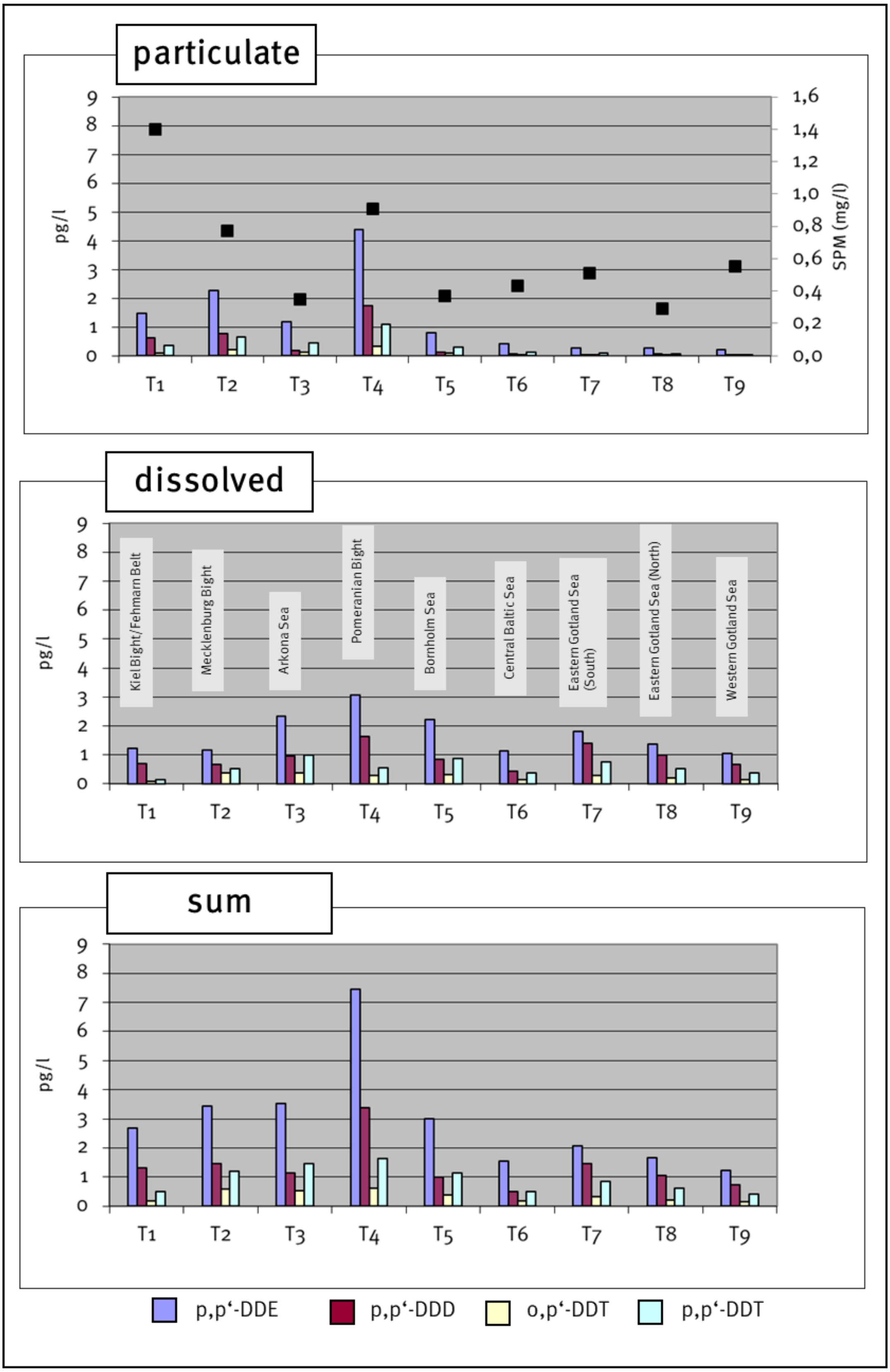

Fig. 35: Concentrations of DDT and its metabolites in the dissolved and particulate fractions of the Baltic Sea surface water samples from the February 2023 observations. Black squares: SPM contents.

Concentrations of *p,p'*-DDT and the metabolite *p,p'*-DDE of past winter observations for the study areas Mecklenburg Bight (T2), Arkona Sea (T3) and Pomeranian Bight (T4) are shown in Fig. 36. Trends of decreasing concentrations continue for both compounds at these sites. Higher annual variations and highest concentrations of *p,p'*-DDE_{sum} can be observed particularly for the Pomeranian Bight which mainly derives from particulate DDE at this site and reflects the particulate transport of DDE by the river Oder into the Baltic Sea.

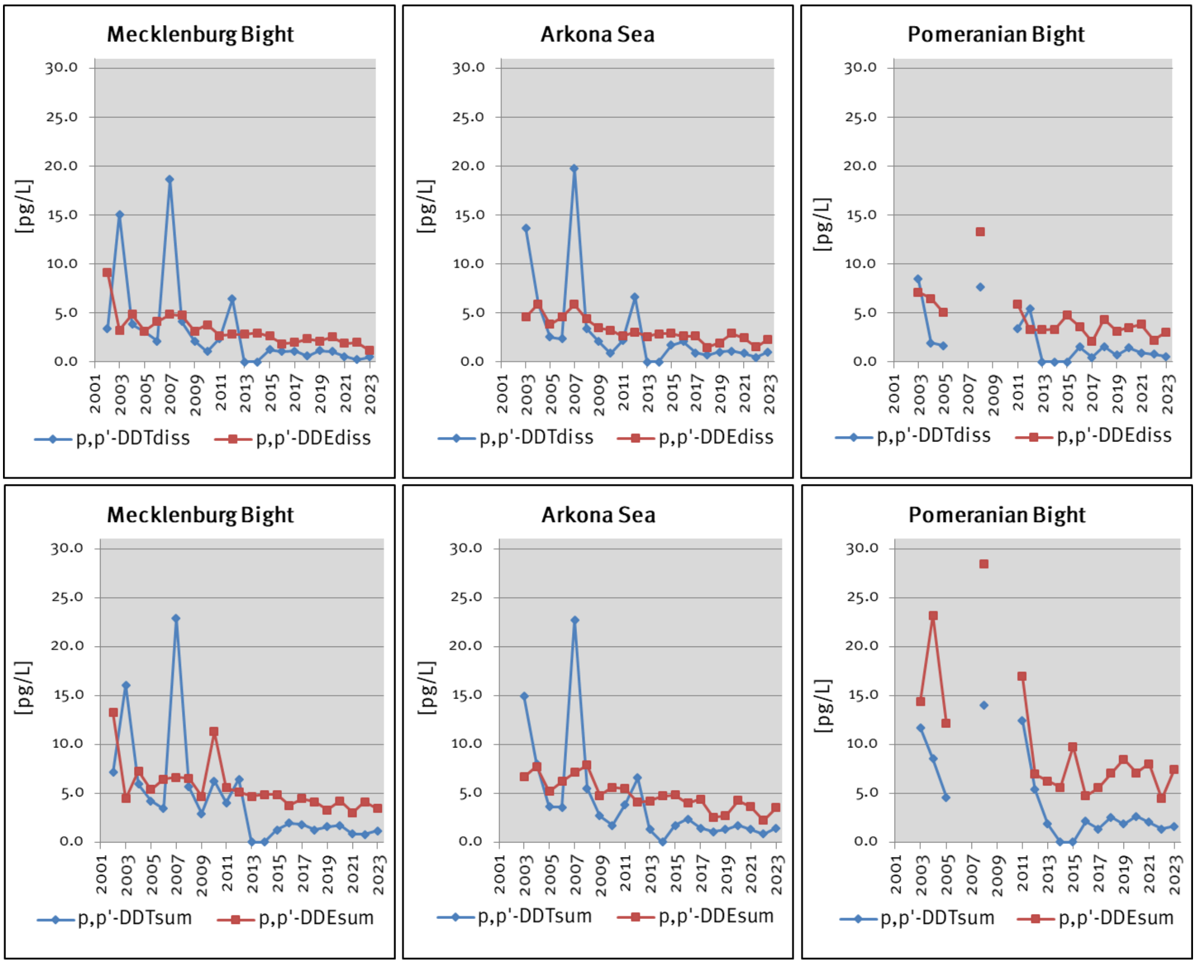

Fig. 36: Time series of p,p'-DDT and p,p'-DDE concentrations in surface water of the Mecklenburg Bight, Arkona Sea and Pomeranian Bight. Upper panel: dissolved water fraction, lower panel: summarized dissolved and suspended water fraction. Gaps in the time line indicate no sampling in the respective year; concentrations at "0 ng l^{-1}" mean that the compound was not detected in the sample.

4.6.2 Results for HCB

In February 2023 concentrations for HCB_{sum}[5] ranged from 4.30 pg l^{-1} in the central Baltic Sea to 11.13 pg l^{-1} in the eastern Gotland Sea (south) (Appendix 4). HCB was mainly found in the dissolved water fractions. The by far highest HCB_{part}[6] concentration of 2.20 pg l^{-1} was obtained for the area Pomeranian Bight.

Developments of HCB concentrations for the study areas Mecklenburg Bight, Arkona Sea and Pomeranian Bight since 2001 are shown in Fig. 37. For the Mecklenburg Bight the in 2023

[5] HCB_{sum}: summarized HCB concentrations of particulate and dissolved water fraction

[6] HCB_{part}: HCB concentrations in the particulate water fraction

obtained data for HCB_{diss} and HCB_{sum} were the lowest within the observed period. A similar observation was not made for the areas Arkona Sea and Pomeranian Bight.

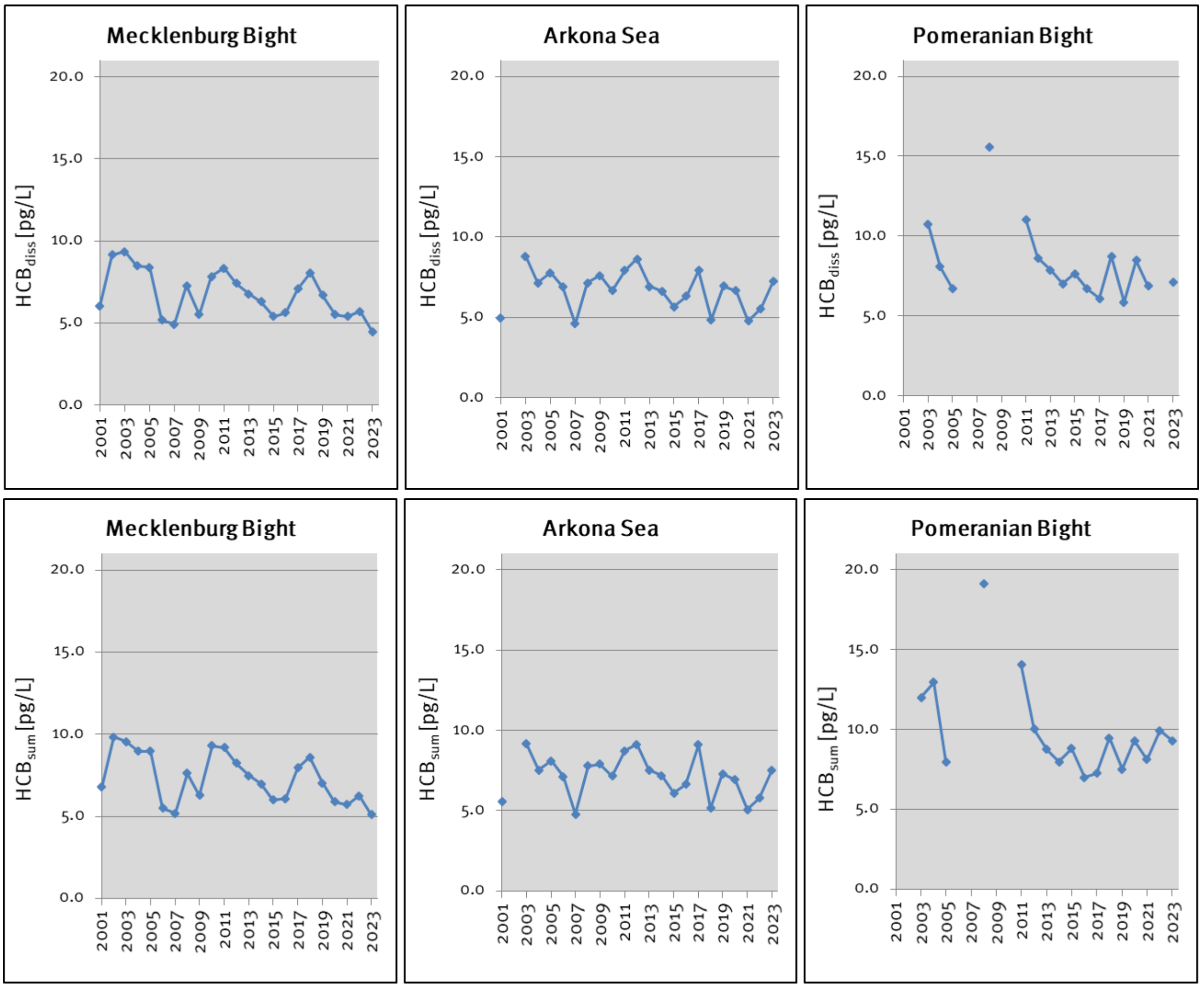

Fig. 37: Obtained concentrations for HCB in Baltic Sea surface water of the Mecklenburg Bight, Arkona Sea and the Pomeranian Bight. Upper panel: dissolved water fraction, lower panel: summarized dissolved and suspended water fraction. Gaps in the time line indicate no sampling in the respective year.

4.6.3 Results for PCB_{ICES}

Obtained winter concentrations for PCB_{ICES} ranged from 1.73 pg l^{-1} ΣPCB_{sum}[7] in the western Gotland Sea (T9) to 8.52 pg l^{-1} ΣPCB_{sum} in the Mecklenburg Bight (Fig. 38, Appendix 3).

Highest concentrations for most PCB_{diss} compounds were obtained for the Mecklenburg Bight (T2). Highest ΣPCB_{sum} concentrations were detected in the areas Kiel Bight/Fehmarn Belt, Mecklenburg Bight and Pomeranian Bight. This largely attributes to high concentrations of particulate PCB (ΣPCB_{part}[8]) in these areas with 4.545 pg l^{-1} for the Kiel Bight/Fehmarn Belt (T1), 3.862 pg l^{-1} for the Mecklenburg Bight (T2) and 4.770 pg l^{-1} for the Pomeranian Bight (T4). At these sites highest SPM concentrations were determined with 1.4 mg l^{-1}, 0.77 mg l^{-1} and 0.91 mg l^{-1}. Here, ΣPCB_{part} have a share of about 62, 45 and 65 % on total PCB, whereas at the other sites the share of ΣPCB_{part} was not more than about 28% indicating the high PCB pressure of the particulate fraction.

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[7] ΣPCB_{SUM}: summarized concentrations of PCB_{ICES} congeners of the dissolved and particulate water fraction

[8] ΣPCB_{part}: summarized concentrations of PCB_{ICES} congeners in the particulate water fraction

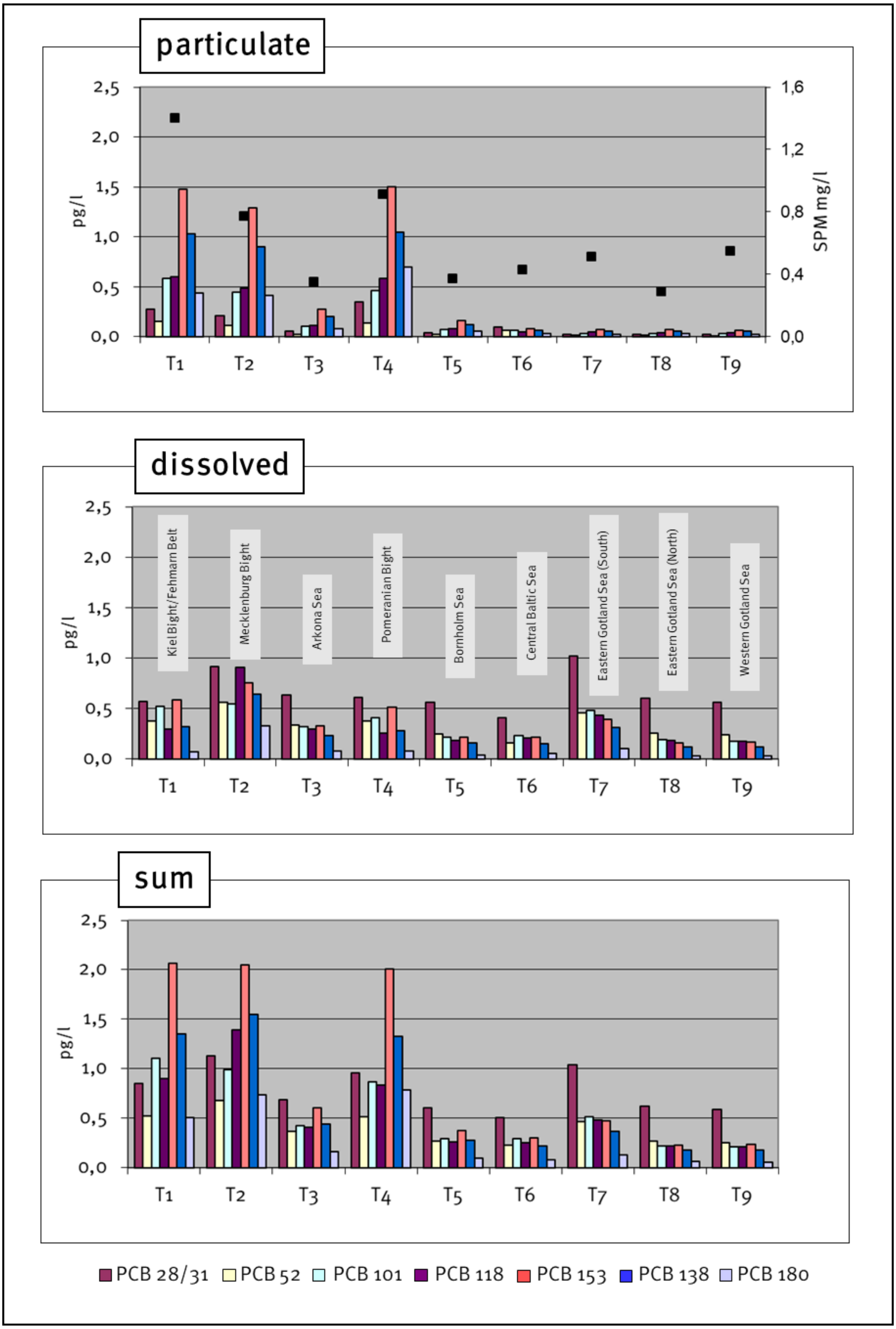

Fig. 38: Concentrations of PCB_{ICES} in the particulate and dissolved water fractions of Baltic Sea surface water in February 2023. Black squares: SPM contents.

Long term observations of past winter concentrations for PCB_{ICES} in surface water for the areas Mecklenburg Bight, Arkona Sea and Pomeranian Bight are shown in Fig. 39. In the Arkona Sea and Pomeranian Bight the decreasing trend continues. For the area Mecklenburg Bight slightly higher concentrations have been observed for the years 2022 and 2023 comparing to the years before.

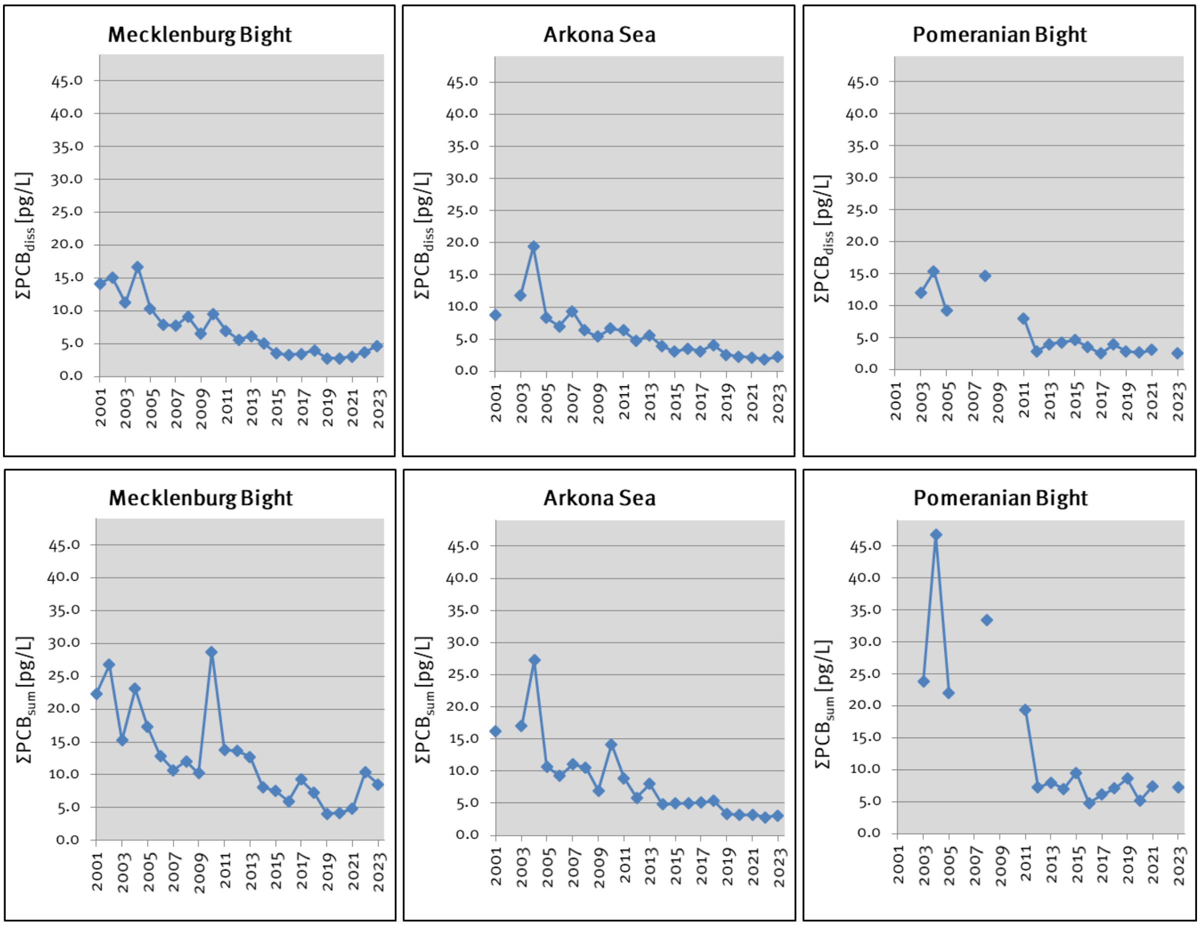

Fig. 39: Time series of ΣPCB_{ICES} concentrations in Baltic Sea surface water at the Mecklenburg Bight, the Arkona Sea and the Pomeranian Bight. Upper panel: dissolved water fraction, lower panel: summarized dissolved and suspended water fraction. Gaps in the time line indicate no sampling in the resp. year.

4.6.4 Results for HEP and HEPEP

In February 2023 dissolved HEP could be detected in the study area of the Mecklenburg Bight (T2, 0.09 pg/L). The more persistent metabolite HEPEP could be detected in all study areas (Appendix 4). HEP and HEPEP were not detectable in the particulate fractions.

Concentrations of $HEPEP_{diss}$[9] ranged from 0.16 pg l^{-1} in the central Baltic Sea to 1.05 pg l^{-1} in the Kiel Bight/Fehmarn Belt (Appendix 4).

[9] $HEPEP_{diss}$: HEPEP concentrations in the dissolved water fraction

4.6.5 Results for PAH

Observed winter concentrations for ΣPAH_{sum}[10] in Baltic Sea surface water ranged from 1293 pg l^{-1} in the central Baltic Sea (T6) to 5150 pg l^{-1} and 4500 pg l^{-1} in the in the Pomeranian Bight (T4) and eastern Gotland Sea (south, T7) (Fig. 40, Appendix 5).

Highest concentrations of ΣPAH_{part}[11] with 2083.6 pg l^{-1} were detected for the Pomeranian Bight indicating a high PAH pressure of the particulate fraction at this site. Similar to the observations for DDT/met., the high SPM concentrations found for the areas T1 and T2 are not reflected in the particulate PAH pressure at these sites.

[10] ΣPAH_{SUM}: summarized U.S. EPA PAH indicator compounds (exc. naph) in particulate and dissolved water fraction

[11] ΣPAH_{part}: summarized U.S. EPA PAH indicator compounds (exc. naph) in particulate water fraction

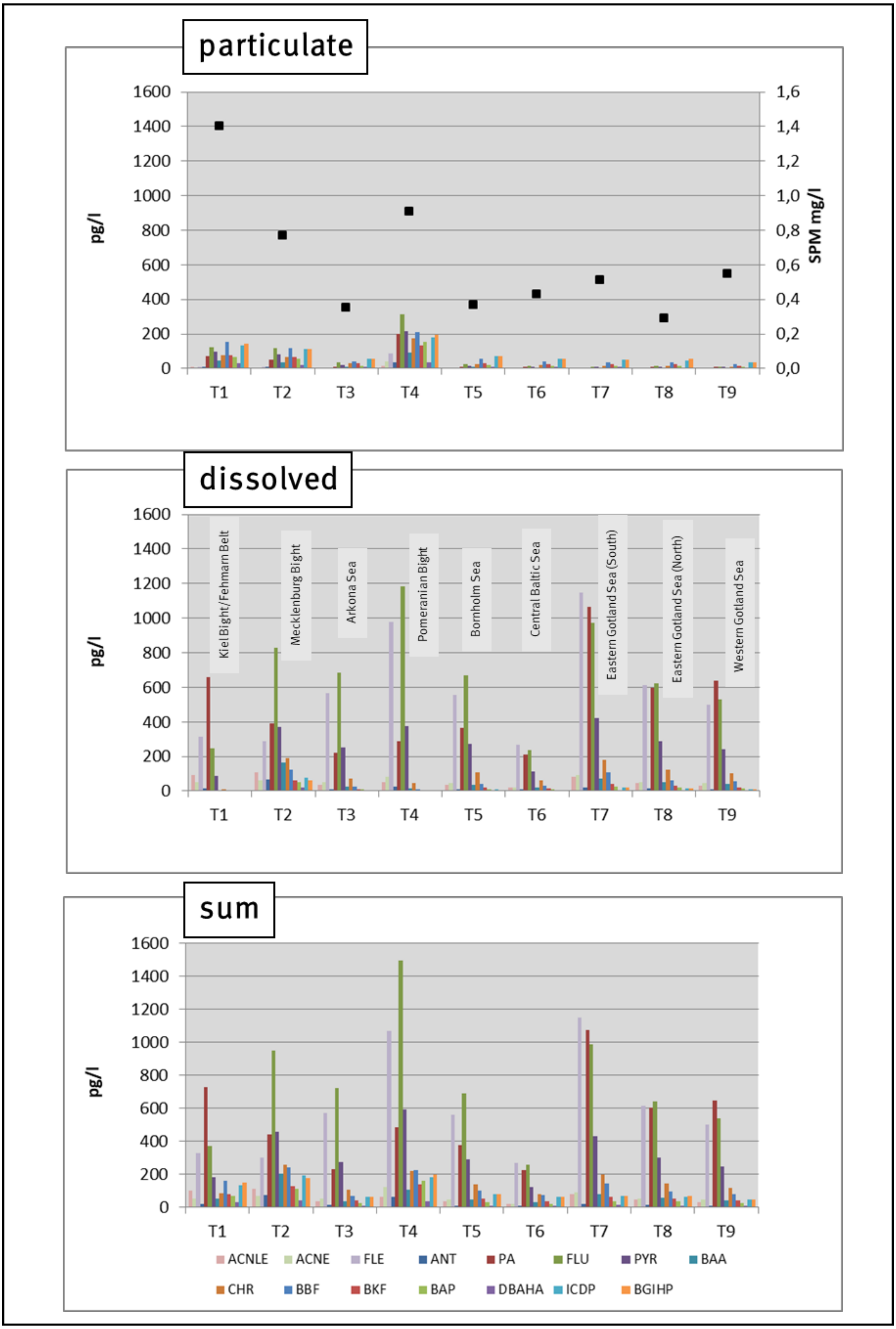

Fig. 40: Concentrations of U.S. EPA PAH (exc. naph) in the dissolved and particulate fraction of Baltic Sea surface waters in February 2023.

Fig. 41 depicts long term observations of PAH concentration for the sites Mecklenburg Bight, Arkona Sea and Pomeranian Bight since 2003. The data set shows high variations of PAH concentrations indicating temporally intense sources. However, the PAH concentrations derived for the year 2023 are among the lowest obtained within the observed period.

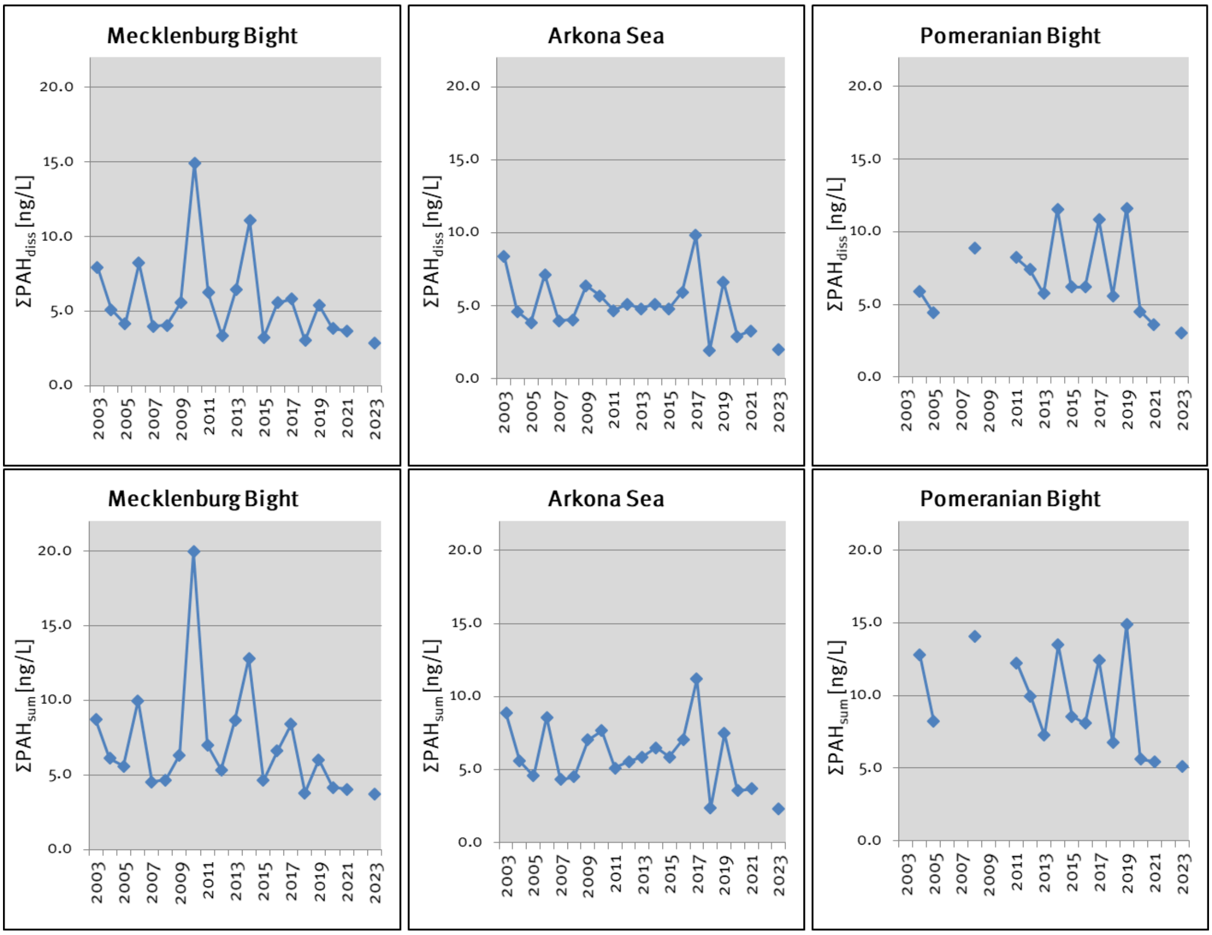

Fig. 41: Time series of concentrations of U.S. EPA PAH (exc. naph) in surface water of the Mecklenburg Bight, the Arkona Sea and the Pomeranian Bight. Upper panel: dissolved water fraction, lower panel: summarized dissolved and suspended water fraction. Gaps in the time line indicate no sampling in the respective year.

4.7 Assessment of the results

Quantitative threshold values for contaminants defining a good environmental status of the Baltic Sea have been defined within the framework of European water policy and the HELCOM commitment. Under European legislation monitoring of hazardous substances in the Baltic Sea is directed through the MSFD[12] and the WFD[13]. The Environmental Quality Standards (EQS) for

[12] Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy

[13] Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy

surface waters of the EQS-Directive[14] serve as the basis to evaluate obtained results for CHC and PAH in Baltic Sea surface water in February 2023.

None of the obtained contaminant data in the Baltic Sea surface water exceeded defined maximum allowable concentrations (MAC-EQS). Determined concentrations for DDT and metabolites, HCB as well as HCH in Baltic Sea surface water also do not exceed annual average EQS (AA-EQS) values.

However, obtained concentrations for HEP in the Mecklenburg Bight and HEPEP in all investigated study areas exceeded the annual average EQS (AA-EQS). Among the analysed PAH compounds, the AA-EQS was exceeded for the high molecular weight PAH compound BBF, BGHIP and ICDP at the sites Mecklenburg Bight (T2) and Pomeranian Bight (T4) (Table 10).

Table 10: Contaminants for which exceedances of Environmental Quality Standards (EQS) of the EQS-Directive were found. Red values: exceeded EQS, AA-EQS: annual average EQS, MAC-EQS: maximum allowable concentration, data for dissolved and particulate water fraction were summarized, n.d. not detected.

Conta-minant	AA-EQS	MAC-EQS	T1	T2	T3	T4	T5	T6	T7	T8	T9
						[µg/L]					
BBF_{sum}	0.00017	0.017	0.00016	0.00024	0.00007	0.00022	0.00010	0.0007	0.00014	0.00010	0.00008
$BGHIP_{sum}$	0.00017	0.0082	0.00015	0.00018	0.00006	0.00020	0.00008	0.00006	0.00007	0.00007	0.00005
$ICDP_{sum}$	0.00017	-	0.00013	0.00019	0.00006	0.00018	0.00008	0.00006	0.00007	0.00006	0.00005
HEP_{sum}	$1 \cdot 10^{-8}$	$3 \cdot 10^{-5}$	n.d.	$9 \cdot 10^{-8}$	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
$HEPEP_{sum}$	$1 \cdot 10^{-8}$	$3 \cdot 10^{-5}$	$105 \cdot 10^{-8}$	$29 \cdot 10^{-8}$	$81 \cdot 10^{-8}$	$97 \cdot 10^{-8}$	$47 \cdot 10^{-8}$	$16 \cdot 10^{-8}$	$86 \cdot 10^{-8}$	$63 \cdot 10^{-8}$	$37 \cdot 10^{-8}$

[14]Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy; amended by directive 2013/39/EU

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Appendix: Organic hazardous substances

Appendix 1: Concentrations of α-, β- and γ-HCH in Baltic Sea surface water in February 2023.

Sampling Sites	Station	Depth [m]	α-HCH	β-HCH [pg/L]	γ-HCH	ΣHCH
Kiel Bight	TF0360/N3	5	24	54	30	108
Fehmarn Belt	TF0010/N1	5	25	59	30	114
Mecklenburg Bight	TF0012/M2	5	28	66	36	130
	TF0046/M1	5	28	77	32	137
Darss Sill	TF0030/K8	5	28	96	31	155
Arkona Basin	TF0069/K7	5	29	102	30	161
	TF0109/K4	5	28	96	30	154
	TF0113/K5	5	30	93	31	154
Pomeranian Bight (north)	TF0152/K3	5	27	92	27	146
Pomeranian Bight	OBBoje/OB	5	34	86	31	151
Bornholm Basin	TF0213/K2	5	28	96	27	151
		80	26	78	23	127
Gotland Deep	TF0271	5	28	96	25	149
		210	33	95	18	146

Appendix 2: Concentrations of DDT and metabolites in Baltic Sea surface water in February 2023.

Dissolved	Transect	*p,p'*-DDE	*p,p'*-DDD	*o,p'*-DDT [pg/L]	*p,p'*-DDT	ΣDDT_{diss}
Kiel Bight/ Fehmarn Belt	T1	1.22	0.69	0.07	0.14	2.12
Mecklenburg Bight	T2	1.16	0.67	0.37	0.52	2.72
Arkona Sea	T3	2.33	0.97	0.39	1.00	4.69
Pomeranian Bight	T4	3.06	1.64	0.27	0.55	5.52
Bornholm Sea	T5	2.21	0.85	0.30	0.86	4.22
central Baltic Sea	T6	1.14	0.42	0.13	0.37	2.06
eastern Gotland Sea (south)	T7	1.80	1.40	0.30	0.76	4.26
eastern Gotland Sea (north)	T8	1.38	0.99	0.19	0.52	3.08
western Gotland Sea	T9	1.04	0.68	0.14	0.37	2.23

Particulate	Transect	*p,p'*-DDE	*p,p'*-DDD	*o,p'*-DDT [pg/L]	*p,p'*-DDT	ΣDDT_{part}
Kiel Bight/ Fehmarn Belt	T1	1.46	0.62	0.106	0.36	2.55
Mecklenburg Bight	T2	2.27	0.77	0.224	0.66	3.92
Arkona Sea	T3	1.20	0.17	0.129	0.45	1.95
Pomeranian Bight	T4	4.39	1.74	0.338	1.09	7.56
Bornholm Sea	T5	0.79	0.13	0.086	0.29	1.30
central Baltic Sea	T6	0.41	0.07	0.039	0.13	0.65
eastern Gotland Sea (south)	T7	0.27	0.05	0.023	0.09	0.43
eastern Gotland Sea (north)	T8	0.27	0.06	0.019	0.08	0.43
western Gotland Sea	T9	0.20	0.04	0.011	0.05	0.30

Sum (dissolved + particulate)	Transect	*p,p'*-DDE	*p,p'*-DDD	*o,p'*-DDT [pg/L]	*p,p'*-DDT	ΣDDT_{sum}
Kiel Bight/ Fehmarn Belt	T1	2.68	1.31	0.18	0.50	4.67
Mecklenburg Bight	T2	3.43	1.44	0.59	1.18	6.64
Arkona Sea	T3	3.53	1.14	0.52	1.45	6.64
Pomeranian Bight	T4	7.45	3.38	0.61	1.64	13.08
Bornholm Sea	T5	3.00	0.98	0.39	1.15	5.52
central Baltic Sea	T6	1.55	0.49	0.17	0.50	2.71
eastern Gotland Sea (south)	T7	2.07	1.45	0.32	0.85	4.69
eastern Gotland Sea (north)	T8	1.65	1.05	0.21	0.60	3.51
western Gotland Sea	T9	1.24	0.72	0.15	0.42	2.53

Appendix 3: Concentrations of PCB$_{ICES}$ in Baltic Sea surface waters in February 2023.

Dissolved	Transect	PCB 28/31	PCB 52	PCB 101	PCB 118	PCB 153	PCB 138	PCB 180	ΣPCB$_{diss}$
					[pg/L]				
Kiel Bight/ Fehmarnbelt	T1	0.57	0.37	0.52	0.30	0.59	0.32	0.072	2.74
Mecklenburg Bight	T2	0.92	0.56	0.54	0.90	0.76	0.64	0.325	4.65
Arkona Sea	T3	0.63	0.34	0.32	0.30	0.33	0.23	0.080	2.23
Pomeranian Bight	T4	0.61	0.38	0.41	0.25	0.51	0.28	0.082	2.52
Bornholm Sea	T5	0.56	0.25	0.22	0.18	0.21	0.16	0.041	1.62
central Baltic Sea	T6	0.41	0.16	0.23	0.21	0.22	0.16	0.052	1.44
eastern Gotland Sea (south)	T7	1.02	0.46	0.48	0.43	0.40	0.31	0.103	3.20
eastern Gotland Sea (north)	T8	0.60	0.26	0.19	0.18	0.16	0.12	0.036	1.55
western Gotland Sea	T9	0.56	0.24	0.18	0.18	0.17	0.12	0.033	1.48

Particulate	Transect	PCB 28/31	PCB 52	PCB 101	PCB 118	PCB 153	PCB 138	PCB 180	ΣPCB$_{part}$
					[pg/L]				
Kiel Bight/ Fehmarnbelt	T1	0.278	0.150	0.584	0.596	1.476	1.027	0.434	4.545
Mecklenburg Bight	T2	0.208	0.115	0.446	0.485	1.292	0.904	0.412	3.862
Arkona Sea	T3	0.053	0.027	0.102	0.109	0.273	0.204	0.081	0.849
Pomeranian Bight	T4	0.346	0.140	0.460	0.585	1.498	1.042	0.699	4.770
Bornholm Sea	T5	0.042	0.024	0.071	0.079	0.161	0.121	0.059	0.557
central Baltic Sea	T6	0.097	0.061	0.066	0.047	0.083	0.065	0.032	0.451
eastern Gotland Sea (south)	T7	0.023	0.012	0.035	0.048	0.073	0.059	0.025	0.275
eastern Gotland Sea (north)	T8	0.022	0.012	0.033	0.042	0.072	0.055	0.029	0.265
western Gotland Sea	T9	0.021	0.010	0.031	0.037	0.067	0.053	0.022	0.241

Sum (dissolved+ particulate)	Transect	PCB 28/31	PCB 52	PCB 101	PCB 118	PCB 153	PCB 138	PCB 180	ΣPCB$_{sum}$
					[pg/L]				
Kiel Bight/ Fehmarnbelt	T1	0.85	0.52	1.10	0.90	2.07	1.35	0.51	7.30
Mecklenburg Bight	T2	1.13	0.68	0.99	1.39	2.05	1.54	0.74	8.52
Arkona Sea	T3	0.68	0.37	0.42	0.41	0.60	0.43	0.16	3.07
Pomeranian Bight	T4	0.96	0.52	0.87	0.84	2.01	1.32	0.78	7.30
Bornholm Sea	T5	0.60	0.27	0.29	0.26	0.37	0.28	0.10	2.17
central Baltic Sea	T6	0.51	0.22	0.30	0.26	0.30	0.23	0.08	1.90
eastern Gotland Sea (south)	T7	1.04	0.47	0.52	0.48	0.47	0.37	0.13	3.48
eastern Gotland Sea (north)	T8	0.62	0.27	0.22	0.22	0.23	0.18	0.07	1.81
western Gotland Sea	T9	0.58	0.25	0.21	0.22	0.24	0.17	0.06	1.73

Appendix 4: Concentrations of HCB, HEPEP and HEP in Baltic surface water in February 2023. n.d. not detected

Dissolved	Transect	HCB	HEPEP	HEP
		pg/L		
Kiel Bight/ Fehmarn Belt	T1	5.4	1.05	n.d.
Mecklenburg Bight	T2	4.5	0.29	0.09
Arkona Sea	T3	7.2	0.81	n.d.
Pomeranian Bight	T4	7.1	0.97	n.d.
Bornholm Sea	T5	5.7	0.47	n.d.
central Baltic Sea	T6	4.1	0.16	n.d.
eastern Gotland Sea (south)	T7	11.0	0.86	n.d.
eastern Gotland Sea (north)	T8	7.9	0.63	n.d.
western Gotland Sea	T9	6.9	0.37	n.d.

Particulate	Transect	HCB	HEPEP	HEP
		pg/L		
Kiel Bight/ Fehmarn Belt	T1	0.55	n.d.	n.d.
Mecklenburg Bight	T2	0.63	n.d.	n.d.
Arkona Sea	T3	0.28	n.d.	n.d.
Pomeranian Bight	T4	2.20	n.d.	n.d.
Bornholm Sea	T5	0.23	n.d.	n.d.
central Baltic Sea	T6	0.20	n.d.	n.d.
eastern Gotland Sea (south)	T7	0.13	n.d.	n.d.
eastern Gotland Sea (north)	T8	0.16	n.d.	n.d.
western Gotland Sea	T9	0.14	n.d.	n.d.

Sum (dissolved+ particulate	Transect	HCB	HEPEP	HEP
		pg/L		
Kiel Bight/ Fehmarn Belt	T1	5.95	1.05	n.d.
Mecklenburg Bight	T2	5.13	0.29	0.09
Arkona Sea	T3	7.48	0.81	n.d.
Pomeranian Bight	T4	9.30	0.97	n.d.
Bornholm Sea	T5	5.93	0.47	n.d.
central Baltic Sea	T6	4.30	0.16	n.d.
eastern Gotland Sea (south)	T7	11.13	0.86	n.d.
eastern Gotland Sea (north)	T8	8.06	0.63	n.d.
western Gotland Sea	T9	7.04	0.37	n.d.

Appendix 5: Concentrations of dissolved and particulate PAH in Baltic Sea surface water in February 2023

Dissolved	Transect	ACNLE	ACNE	FLE	ANT	PA	FLU	PYR	BAA	CHR	BBF	BKF	BAP	DBAHA	ICDP	BGHIP	ΣPAH_{diss}
									[pg/L]								
Kiel Bight/ Fehmarnbelt	T1	93	51	314	13.4	658	245	87	4.5	11.0	7.4	2.3	1.1	0.33	0.92	0.97	1489.9
Mecklenburg Bight	T2	108	63	287	67.6	389	827	373	165.6	188.5	123.2	63.9	53.3	20.69	78.38	61.29	2869.5
Arkona Sea	T3	35	53	567	10.8	220	686	252	22.9	74.0	27.6	12.1	7.5	1.44	6.29	6.18	1981.8
Pomeranian Bight	T4	50	80	980	26.6	286	1184	376	15.0	44.9	11.5	4.7	3.1	0.64	2.16	2.13	3066.7
Bornholm Sea	T5	36	45	554	10.0	364	666	274	37.6	110.1	40.0	21.6	11.6	1.58	8.19	7.15	2186.8
central Baltic Sea	T6	18	20	267	7.5	212	239	112	20.7	59.5	30.6	13.2	7.9	1.17	6.02	6.02	1020.6
eastern Gotland Sea (south)	T7	80	92	1148	19.9	1063	975	422	71.1	180.0	105.8	41.7	25.1	3.98	20.58	19.48	4267.6
eastern Gotland Sea (north)	T8	46	53	613	14.2	594	624	288	51.1	124.5	60.4	30.5	21.8	2.79	15.50	14.26	2553.1
western Gotland Sea	T9	31	45	501	9.6	638	528	239	38.4	102.9	55.9	22.6	15.5	2.13	12.31	11.07	2252.4

Particulate	Transect	ACNLE	ACNE	FLE	ANT	PA	FLU	PYR	BAA	CHR	BBF	BKF	BAP	DBAHA	ICDP	BGHIP	ΣPAH_{part}
									[pg/L]								
Kiel Bight/ Fehmarnbelt	T1	7.5	3.2	10.8	8.78	70.1	124.2	96.8	45.0	75.4	153.3	75.0	65.5	28.8	131.1	146.2	1041.7
Mecklenburg Bight	T2	3.3	2.9	11.2	7.47	49.8	119.7	84.2	35.3	67.2	115.9	65.3	56.9	20.2	114.6	114.5	868.5
Arkona Sea	T3	1.1	0.7	3.6	1.59	11.5	33.7	21.7	10.7	31.0	42.3	28.4	17.3	8.6	56.1	56.8	325.1
Pomeranian Bight	T4	15.1	42.5	85.4	37.68	198.2	311.7	214.8	93.0	174.6	211.8	135.2	156.2	34.4	179.0	194.1	2083.6
Bornholm Sea	T5	1.1	0.6	2.7	1.03	10.0	23.7	16.8	10.2	27.8	57.9	32.3	19.2	9.7	70.4	70.1	353.5
central Baltic Sea	T6	0.8	0.8	2.6	0.71	12.0	17.0	11.9	7.2	20.1	40.3	25.1	14.0	7.6	55.3	56.0	271.4
eastern Gotland Sea (south)	T7	0.9	0.5	1.4	0.62	7.2	12.1	8.9	6.3	16.5	35.5	23.5	13.2	7.8	48.7	50.7	233.8
eastern Gotland Sea (north)	T8	0.9	0.6	1.7	0.67	7.7	13.2	9.9	6.6	16.8	36.0	22.9	14.1	7.0	48.3	54.2	240.6
western Gotland Sea	T9	0.7	0.5	1.3	0.68	8.2	10.5	7.7	4.8	11.9	25.4	16.6	9.8	5.0	35.3	36.7	175.1

Table Appendix 5 *continued*

Sum (particulate + dissolved)	Transect	ACNLE	ACNE	FLE	ANT	PA	FLU	PYR	BAA	CHR	BBF	BKF	BAP	DBAHA	ICDP	BGHIP	ΣPAH$_{sum}$
									[pg/L]								
Kiel Bight/ Fehmarnbelt	T1	101	54	325	22.2	728	369	184	50	86	161	77	67	29.1	132	147	2532
Mecklenburg Bight	T2	111	66	298	75.1	439	947	457	201	256	239	129	110	40.9	193	176	3738
Arkona Sea	T3	36	54	571	12.4	232	720	274	34	105	70	41	25	10.0	62	63	2309
Pomeranian Bight	T4	65	123	1065	64.3	484	1496	591	108	220	223	140	159	35.0	181	196	5150
Bornholm Sea	T5	37	46	557	11.0	374	690	291	48	138	98	54	31	11.3	79	77	2542
central Baltic Sea	T6	19	21	270	8.2	224	256	124	28	80	71	38	22	8.8	61	62	1293
eastern Gotland Sea (south)	T7	81	93	1149	20.5	1070	987	431	77	197	141	65	38	11.8	69	70	4500
eastern Gotland Sea (north)	T8	47	54	615	14.9	602	637	298	58	141	96	53	36	9.8	64	68	2794
western Gotland Sea	T9	32	46	502	10.3	646	539	247	43	115	81	39	25	7.1	48	48	2428

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CONTENT

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