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Deep water of the Gdansk Deep (Baltic Sea): development over the last 20 years

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Abstract. This study examines the development of the deep layer of the Gdansk Deep in the Baltic Sea over the past 20 years (2003–2023), with a focus on changes in dissolved oxygen levels and hydrological parameters following major Baltic inflows (MBIs) in 2003 and 2014 The Gdansk Deep has experienced significant changes within deep layer in 2003–2023, with increasing temperature, stable salinity, and decreasing dissolved oxygen content. The temperature increases in the deep layer of the Gdansk Deep may be attributed to increased number of warm summer inflows and global ocean temperature rise. Data from environmental monitoring and various sources was used to describe seasonal and interannual variations in dissolved oxygen concentration and suggests potential additional sources of oxygen apart from MBIs, including deep convection and intra-pycnocline intrusions.

1 Introduction

The Baltic Sea is particularly sensitive to both natural and anthropogenic impacts due to its unique characteristics, which distinguish it from other water bodies (Dybern and Fonselius, 1981; HELCOM, 2023; Lehtonen et al., 2006; Meier et al., 2022; Viitasalo and Bonsdorff, 2022). The pronounced stratification, which has been increasing in recent decades (Liblik and Lips, 2019), and the permanent halocline (and with it the pycnocline) interfere with vertical mixing of deep and surface waters, limiting atmospheric oxygen supply to the deep layer. Thus, aeration of main deep water occurs predominantly through an advective input of transformed water from the North Sea: Major Baltic Inflows (MBI) (Matthäus and Franck, 1992; Feistel et al., 2010; Mohrholz et al., 2015; Mohrholz, 2018), including small volume inflows (Feistel et al., 2010), and intra-picnocline intrusions (Väli et al., 2017; Holtermann et al., 2020). Some evidence suggests that oxygen supply to the deep layer associated with intra-pycnocline intrusions may be an order of magnitude higher than during MBIs (Holtermann et al., 2020). Oxygen supply through the halocline is related to mesoscale processes and is governed by halocline position and gradient (Väli et al., 2017; Zhurbas and Paka, 1997; Conley et al., 2009). For instance, convective mixing in the Słupsk Furrow, through which transformed MBIs water propagates further into the Gdansk and Gotland Deeps (Schmidt et al., 2021; Golenko et al., 2023), can be observed up to the bottom (70 m) (Piechura and Beszczynska-Moller, 2003) without significant halocline interference, creating aerated intra-pycnocline intrusions.

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The most recent MBI, the third largest in the history of observations (Mohrholz, 2018; Meier et al., 2022), occurred at the end of 2014. Some observations indicate that less dissolved oxygen (DO) was delivered to the central Baltic during this inflow than during the smaller inflow of 2003, and oxygen concentrations in the bottom layer of the Słupsk Furrow decreased to less than 2 mg/l in 10 months (Neumann et al., 2020).

The rapid consumption of oxygen supplied with the inflow, and the associated increase in the area of hypoxic and anoxic (even euxinic i.e. rich with hydrogen sulfide) zones in deep areas of the Baltic Sea, including the Gdansk Deep (Mohrholz, 2018; Meier et al., 2022), is attributed to a number of natural and anthropogenic factors. Eutrophication of the water body (Zillén et al., 2008; Conley et al., 2009; Savchuk, 2018), increased oxygen deficit associated with the consumption of oxygen for NH_4 and H_2S accumulated during the period without MBIs (Rolff et al., 2022). The higher deep layer temperatures observed in recent years (Kniebusch et al., 2019; Kankaanpää et al., 2023) accelerate mineralisation of organic matter in sediments, leading to increased oxygen consumption (Laufkötter et al., 2017; Krapf et al., 2022). At the same time, DO consumption may be slower in intermediate layers, which is associated with more regular smaller inflows, which may lead to an increased importance of intra-pycnocline and sub-halocline intrusions in maintaining the ecological well-being of the Baltic Sea.

This research seeks to identify temporal variations in DO levels and hydrological parameters after two MBIs (2003 and 2014). The Gdansk Deep (Fig. 1) is one of the Baltic Sea areas, that severely suffers from hydrogen sulfide presence in the deep layer, harming bottom communities. At the same time, euxinic area did not significantly grow after the last MBI, so the main goal of this work is to describe seasonal and interannual variability of DO concentration in the deep layer and determine potential sources of oxygen for it apart from MBIs.

2 Materials and Methods

Our studies were carried out in the south-eastern part of the Baltic Sea, which made it possible to describe the current ecological state of the Gdansk Basin. Our data array was obtained during the environmental monitoring held by the Atlantic Branch of the Shirshov Institute of Oceanology of the Russian Academy of Sciences (AB IO RAS) and Sea Venture Bureau (SVB) in 2003–2023 (hereinafter – monitoring data). Dissolved oxygen distribution above slopes of the Gdansk Deep (northern and southern) was studied during a shorter period, starting in 2015 for the northern slope (point 1) and 2020 for the southern slope (point 3), accordingly (Fig. 5). The vast majority of measurements within years 2003–2013 were taken in summer period, so we used additional data source. The additional data set was supplemented with ISEC (International Council for the Exploration of the Sea) (ICES) data in the public domain. In total, more than 630 DO measurements were carried out during the monitoring in the Russian Exclusive Economic Zone (EEZ), and 3600 ICES measurements were used. Monitoring data was gathered at three points within the EEZ: the first one was located at the bottom of the northern slope of the Gdansk Deep, the second — in the central part of the Deep, the third — at the steep south-eastern slope. ICES stations were mostly located within the Polish EEZ (Figure 1). The data were combined into one array due to the homogeneity of hydrological conditions in the deep layer within the 100-m isobath. To analyze the interannual variability of temperature and salinity of the deep layer, field data were averaged in the range of 100–110 m. A total of 35 CTD soundings performed in 2003–2023 were included in the analysis

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during monitoring, 54 CTD soundings – from the ICES database; more than 10 thousand values were obtained from model data from 1993 to 2023 NEMOv4.0 (Baltic Sea Physics Reanalysis, 2024) at coordinates 54.84 °N and 19.319–19.347 °E at depth 104 m. The volumes of salt water entering the Baltic Sea as MBIs (in Gt of salt) in January 2003–2024 were obtained from the database of the Baltic Sea Institute in Warnemünde (Mohrholz, 2018).

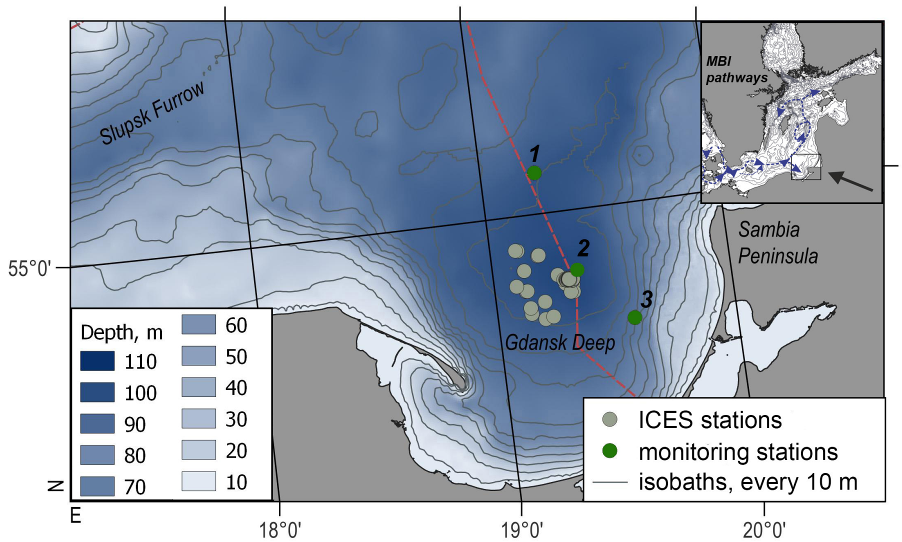

Figure 1. Study area with ICES and AB IO RAS monitoring points. Numbers are for AB IO RAS points. Blue arrows indicate MBI pathways according to (Feistel et al., 2016)

During the monitoring sampling DO concentrations were obtained with a use of modified Winkler method (Strickland and Parsons, 1972). All samples were treated immediately after obtaining them with a use of Hydrobios MWS 12 Slimline. Dissolved hydrogen sulfide concentrations were calculated from dissolved sulfide measurement with a use of NN-diemethyl-p-phenylenediamine and zinc acetate (Grasshoff et al., 2007). Seasonal variability of the oxic-anoxic conditions in the central part of the Gdansk Deep is based on station data obtained during environmental monitoring cruises and supplemented with data from the ICES database. All data are unified: oxygen and hydrogen sulfide are given in ml/l. Dissolved hydrogen sulfide in expressed as negative oxygen as given in (Fonselius, 1969).

Measurements of thermohaline structure parameters were carried out by hydrophysical probes Sea&Sun Tech CTD90M and Idronaut 316 Plus. The characteristics of the probes are presented in Tables 1 and 2. Both probes were operated in the mode of autonomous data recording on the inbuilt digital storage device (Table 1). Water samples were obtained via Multi Water Sampler MWS 12 Slimline, technical data mentioned in Table 1.

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Table 1. Hydrological probes, used during the study

Probe	Sea&Sun Tech CTD90M		Idronaut 316 Plus		MWS 12 Slimline	
Parameter	Range	Accuracy	Range	Accuracy	Range	Accuracy
Conductivity, mSm/m	0–65	0,02	0–70	0,003	0–65	0,01
Temperature, °C	2–36	0,005	-3–50	0,002	-2–32	0,005
Pressure, dbar	0–500	0,1%	0–1000	0,0%	0–3000	< 0.1%

3 Results

3.1 Hydrological parameters within the Gdansk Deep in 2003–2023

An increase in both temperature and salinity in the deep layer of the study area (Fig. 1) was observed within last three decades (1993–2023), such a result was confirmed via field data and NEMO modeling data (Baltic Sea Physics Reanalysis, 2024) (Fig. 2). Over the past 20 years, according to monitoring data, salinity has decreased slightly.

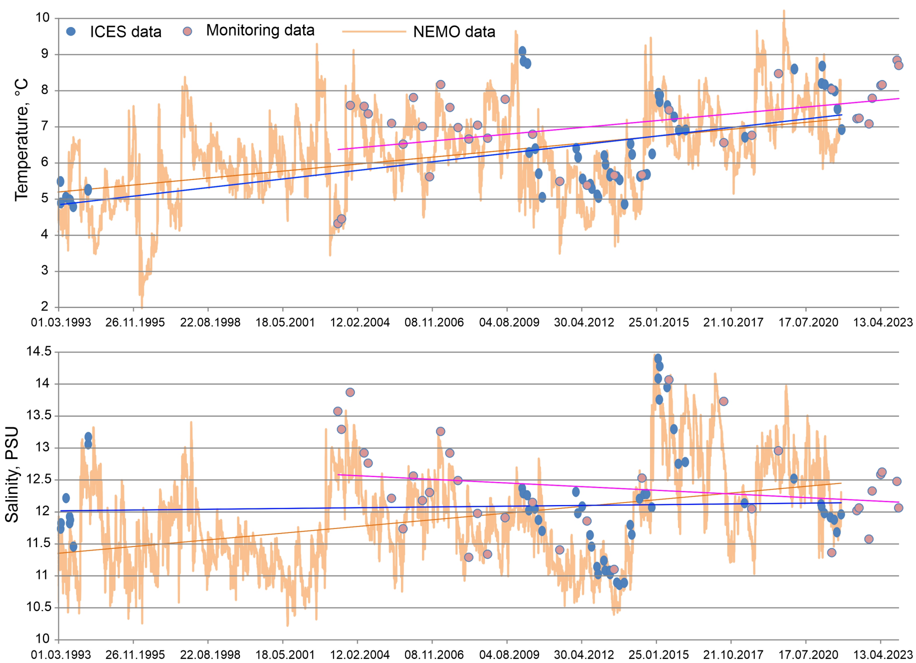

Figure 2. Long-term variability of temperature and salinity in the deep layer of the Gdansk Deep according to field data

The lowest temperature in the deep layer according to various sources was observed in March 1996 as 2.0°C (NEMO), in September 1993 as 4.77°C (ICES) and in May 2003 as 4.32°C (monitoring). The highest temperature according to various sources was observed in October 2019 up to 10.2°C (NEMO), in February 2010 up to 4.77°C (ICES) and in November 2023 up to 4.32°C (monitoring). The salinity of the deep layer according to NEMO model varied over a wider range (from 9.36 PSU

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in March 1993 to 14.45 PSU in January 2015) than according to field data (ICES: from 10.86 PSU in September 2013 to 14.40 PSU in February 2015; monitoring: from 11.10 PSU in July 2013 to 14.07 PSU in July 2015), while the trends in changes of this parameter are similar (Table 2). According to NEMO model data, from 1993 to 2023, the temperature in the deep layer increased by 1.8°C, and salinity by 1.05 PSU.

Table 2. Mean values of the deep layer of the Gdansk Deep according to NEMO, ICES and monitoring data

Dataset	Time range	Data range (mean value)		Linear trend equation for the period	
		T	S	T	S
NEMO	01.03.1993-31.12.2021	2.00-10.20 (6.20)	9.36-14.46 (11.89)	y = 0.0002x-1.3393	y = 0.0001x+7.7804
ICES	01.04.1993-07.04.1994 26.02.2010-03.11.2021	4.78-9.08 (6.41)	10.86-14.40 (12.10)	y = 0.0002x-3.2657	y = 1E-05x+11.612
monitoring	27.05.2003-13.12.2023	4.32-8.84 (7.02)	11.10-14.07 (12.39)	y = 0.0002x-0.7386	y = -6E-05x+14.742

Averaged temperature and salinity for the deep layer of the Gdansk Deep varies in all three data sources. NEMO model showed the lowest bottom salinity (11.89 PSU) and temperature (6.20 °C), monitoring data showed the highest (12.39 PSU and 7.02 °C, accordingly).

The last iteration of an MBI cycle started in 2014, when one of the biggest MBIs occurred. The average salinity in the deep layer of the Gdansk Deep was about 11 PSU, the average temperature — about 5.6°C before this MBI (at the beginning of 2014). The 2014 MBI has caused a sharp rise in temperature and salinity for the deep layer up to the highest values since 2003 — 14.4 PSU and 7.8 °C at a depth of 105 m (February 19, 2015). A steady decrease in salinity was observed afterwards: up to 13.7–13.8 PSU in August 2015 and 12.9 PSU in November 2015. The deep layer temperature also decreased up to 7.5 °C in August and up to 7 °C in November 2015.

Salinity and temperature in the studied deep layer rose to over 14.2 PSU and 7.4 °C, respectively by the end of March 2016. Salinity levels dropped from 13.8 to 13.3 PSU, and temperature decreased from 7.2 to 6.9 °C during the summer of 2016. Salinity in the deep layer of the Gdańsk Deep increased to 13.9 PSU by May 2017. It remained the highest salinity level till the end of 2023.

3.2 Dissolved oxygen within the Gdansk Deep in 2003–2023

As a result of climate change, the temperature of surface water of the Baltic Sea has risen, resulting in the decrease in the solubility of oxygen in the water (Bopp et al., 2013). The temperature of the deep layer is also rising (fig. 2), thus DO content within the deep layer is influenced by both temperature rise and excessive organic matter supply due to eutrophication. Below the halocline (which is located at 60–70 m depth), dissolved oxygen concentration drops sharply from 6–7 ml/l to hypoxic (<2 ml/l) and even anoxic/euxinic (no oxygen or hydrogen sulfide presence) conditions in the deep layer (fig. 3). The Figure 3 represents not only DO concentrations, but also hydrogen sulfide concentrations, which are shown as negative oxygen. Both MBIs (2003 and 2014) caused an aeration of the deep layer, yet the 2003 MBI aeration lasted longer even despite the fact

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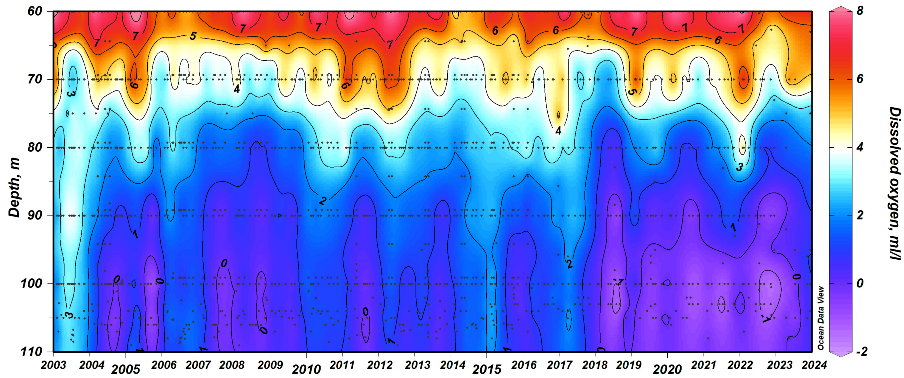

Figure 3. Time course of dissolved oxygen (ml/l) and dissolved hydrogen sulphide content as negative oxygen (ml/l)

that volume of the 2003 MBI was lower than the 2014 one (Mohrholz, 2018). Moreover, euxinic conditions were present in the deepest part of the Gdansk Deep only during late summer – middle autumn period, while since 2019 euxinic water was present almost consistently until November-December 2023, when DO concentration reached 1 ml/l not after the MBI event. There were also short-term periods, when hydrogen sulfide maximum (i.e. negative oxygen minimum) was located not above the bottom itself, but was concentrated within the intermediate layer 10 meters above the bottom. The most aerated month is April.

An overall decrease in DO content within the deep layer (100 m and deeper) of the study area was observed within last two decades (2003–2023), such a result was confirmed via both arrays of field data (Fig. 4, Table 3).

Table 3. Mean oxygen concentration of the deep layer of the Gdansk Deep according to ICES and monitoring data

Dataset	Time range	Data range	Mean value	Linear trend equation for the period
ICES	04.02.2003-10.11.2022	-2.70-3.97	1.01 only DO/0.75 with negative oxygen	y = -0.0002x+9.11
monitoring	27.05.2003-07.03.2024	-4.30-4.97	1.12 only DO/0.73 with negative oxygen	y = -0.0003x+12.624

Thus, we observed a decrease in DO concentration in the absence of a significant decrease in salinity values over the period 2003–2023 for the deep layer of the Gdansk Deep. Similar trends were noted in Gotland and Bornholm Deeps (Mohrholz, 2018). The DO content between two MBI events did not decrease uniformly, but has intra-annual dynamics with minimums in the summer-autumn period. However, a permanent euxinia was observed in the deep layer of the Gdansk Deep since 2019 until the late autumn of 2023, when, even in the absence of a MBI, the DO concentration in the deep layer has risen up to 1 ml/l, indication the presence of an additional source of DO and the inapplicability of the term stagnation for this region.

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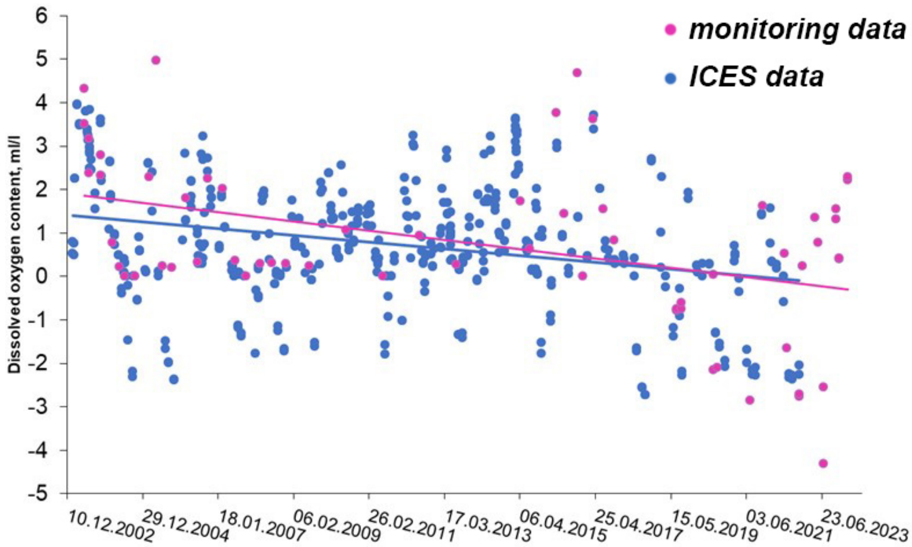

Figure 4. Long-term variability of dissolved oxygen content (including negative oxygen, calculated with hydrogen sulfide content) in the deep layer of the Gdansk Deep according to field data (ICES — blue dots, monitoring — pink dots).

120 ## 4 Discussion

The temperature of the deep layer in recent years has shown the highest values — about 8–9°C, which may be related both to the observed trend of increasing frequency of warm summer inflows and decreasing frequency of winter inflows (Barghorn et al., 2023), and to the observed increase in global ocean temperatures. The noted increase in temperature in the studied water area is also observed for the surface layer of the Baltic and North Seas (Department, 2024). With time, the heat spreads
125 downward through different processes, such as lateral inflows, vertical downwelling, and diffusion, and eventually the whole water column warms up (Meier et al., 2022). Thus the increase in SST is reflected in the increase in temperature of the deep layer of both the Gdansk and Gotland basins (Liblik et al., 2018; Meier et al., 2022), which can also be reflected in a decrease in the solubility of dissolved oxygen throughout the entire water column.

Despite the main growth trend, which is notable in other basins of the Baltic Sea, the Gdansk Deep was also experiencing
130 periods marked by lower temperatures in the deep layer (Fig. 2): from 2010 to 2014. To investigate the possible reasons for this, the temperature values during this period in the cold intermediate layer (CIL) were studied (Fig. 5). Due to the greater solubility of oxygen in cold water, CIL is an oxygen reservoir for the less oxygenated upper and lower layers (Rak et al., 2020). The CIL temperature, as a rule, depends on the severity of winters: the colder the winter, the lower the CIL temperature (Liblik and Lips, 2019) and is highly correlated with the North Atlantic oscillation index (Jones et al., 1998) and Baltic Sea Index
135 (Lehmann et al., 2002).

Thus, from 2010 to 2014, the CIL temperature was significantly lower than the average for 2003–2023, which could also affect the temperature of the deep layer during this period due to diffuse and convective water exchange. Also, lower temper-

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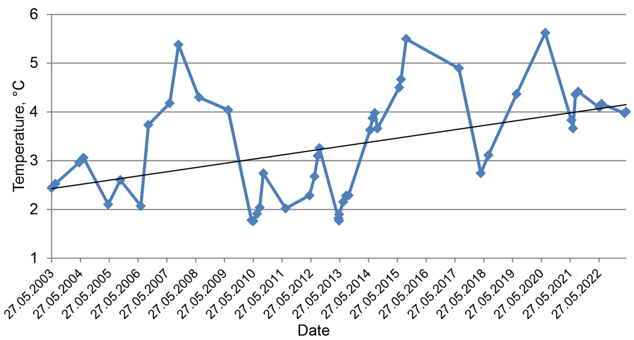

Figure 5. Long-term variability of temperature in the cold intermediate layer of the Gdansk Deep according to field monitoring data.

atures of the deep layer during this period may be associated with lower surface temperatures in the area of the Danish Straits and the North Sea in these years (Meier et al., 2022), water from where is dense and saline, so it propagates as intrapycnocline intrusions. A similar situation was noted in 2018, when, decrease in both CIL and deep temperature was observed (fig. 2 and fig.5). Apparently, the increase in deep water temperature observed in recent years within the Gdansk Deep can be partly explained by CIL temperature rise due to established mildness of winters and a change in the atmospheric circulation index.

Deep layer salinity within the Gdansk Deep experienced quasi-decadal cycles during the study period, which are caused by MBIs. The mean salinity in the area was relatively stable: obtained from the NEMO model average salinity values for the deep layer (11.89 PSU) for 1993–2021 are similar to data from 1998 to 2010 for the Polish part of the Gdansk Basin (11.91 PSU) (Rak et al., 2020), which indicates the continuation of the advective supply of saline water into this part of the sea in the last decade.

The December 2014 MBI played an important role in improving the ecological conditions in the deep layer of the Gdansk Deep. Transformed inflow water reaches the Gdansk Deep in 2–4 months after passing through the Danish Straits (Piechura and Beszczynska-Moller, 2003; Rak, 2016). Thus, the maximum values of deep salinity (14.2 PSU) observed at the beginning of 2015 were noticeably higher than the long-term average (1952–2005), namely, 11.43 PSU, according to (Feistel et al., 2008). Series of subsequent inflow events recharge the Gdansk Basin's deep layer, and salinity and temperature did not drop to the 2013 values, being at about 12 PSU in 2020–2022 (Fig. 6).

The DO concentration has pronounced decreasing trend within the observed period (fig. 4), which contradicts with the stable salinity level, while MBIs are the main source of both oxygen and salt into the deep layer of the deep regions of the Baltic Sea. Eutrophication is named to be the main reason of rapid consumption of DO supplied with the MBIs (Mohrholz, 2018; Meier et al., 2022; Rolff et al., 2022).

The interannual variability of deep layer's temperature and salinity in the deep part of the study area (depth more than 70 m) does not have a pronounced seasonal pattern. DO pattern, on the other hand, has a seasonal variability in addition to overall decrease. Higher concentrations of DO in the near-bottom layer of the Gdansk Deep were observed in the winter-spring period, lower ones — in the summer-autumn, which coincide with results, obtained in (Krapf et al., 2022) for the Eastern Gotland and Bornholm Basins. The presence of a seasonal cycle of DO in the deep layer, as well as the high tightness of the synchronous

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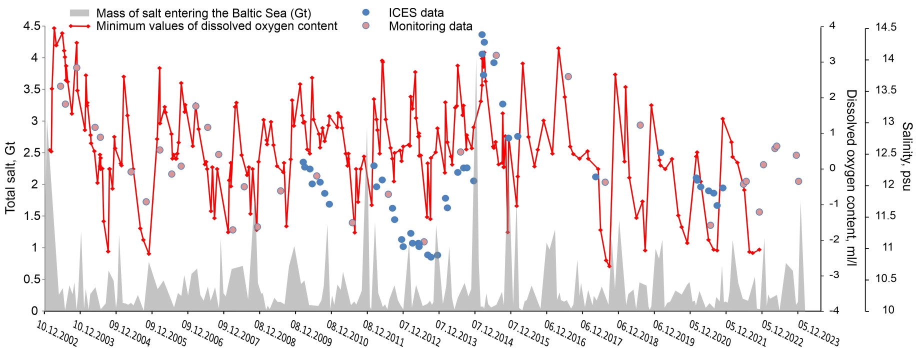

Figure 6. Salinity in the deep layer of the Gdansk Deep for the period from 2002 to 2024 according to ICES data and obtained in expeditions of the monitoring.

relationship between the content in the surface and bottom layers, was also shown for 1969–2017 (Dubravin, 2021). There are several reasons for a seasonal cycle. According to Krapf et al. (2022) DO minimum is caused by increased oxygen depletion that follows spring and summer algal blooms, producing organic matter, which have to be decomposed. Winter-spring aeration may be the result of interleaving of oxygenized intrusions to the hypoxic transition zone (Holtermann et al., 2020; Golenko et al., 2023), which is potentially responsible for the occurrence of intermediate layers of hydrogen sulfide maxima, which are detached from the bottom. These intrusions of oxygen-rich water occur most likely due to the ventilation of the Slupsk Furrow, that is acknowledged as one of a primary mixing zones of inflowing waters, exhibiting the phenomenon of entrainment from both surface and intermediate waters, during the winter and the subsequent eastward spread of these waters due to inflows of lesser intensity than the MBI (Kouts and Omstedt, 1993).

However, the period between 2019 and 2023 was characterized by uniformed presence of euxinic conditions without a pronounced seasonal variability. Progressive disappearance of seasonal variability in two last decades was first shown in Schmidt et al. (2021). Such situation had lasted until November-December 2023, when DO concentrations surged up to 1 ml/l. Thus, to investigate other possible mechanisms of oxygen supply to the deep layer in the autumn-winter period, depth-time graphs were made for points at the slopes of the Gdansk Deep (points 1 and 3 at Fig. 1). The deep layer at the point 1 experienced hydrogen sulfide presence as well as the central part of the Gdansk Deep (Fig. 7 a). At the same time, southern slope (point 3, Fig. 1) showed no H_2S presence at all (Fig. 7 b) due to shallower depth (80 m compared to 100 m). Winter of 2023 was distinct by the fact that DO concentrations in the deep layer at point 3 were higher than hypoxia limit (2 ml/l).

Exceptionally high DO values in the deep layer in November-December 2023 may be potentially caused by observed incidents of deep convection above the steep southern slope of the Gdansk Deep, where a mixed layer depth is able to reach 70 m depth (Figure 8). The mixed layer depth in the period November-December 2021–2023 ranged from 35 m in November 2022 to more than 70 m in December 2023, while the average MLD estimates in this part of the sea are 60 m (Bulczak et al., 2024). Such deep convection may be one of the mechanisms for the dissolved oxygen supply the halocline layer of the Gdansk Deep and even deeper, if halocline is not strong enough (Lehmann et al., 2022). Thus, halocline penetrating salt fluxes are regulated

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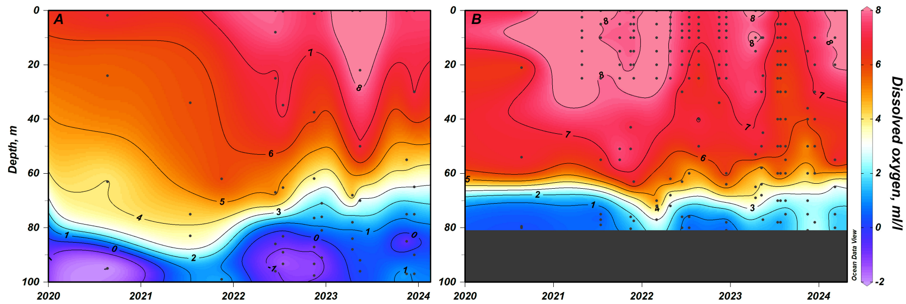

Figure 7. Time course of dissolved oxygen (ml/l) and dissolved hydrogen sulphide content (as negative oxygen (ml/l)) at point 1 (A) and point 3 (B), points location was shown on Fig. 1

via mechanical mixing, convection and vertical advection. According to Neumann et al. (2020) lateral inflows or ventilation due to convection are possible mechanisms for high oxygen concentrations in the deep water in the regions where the salinity stratification is weak, i.e. northern Baltic Sea.

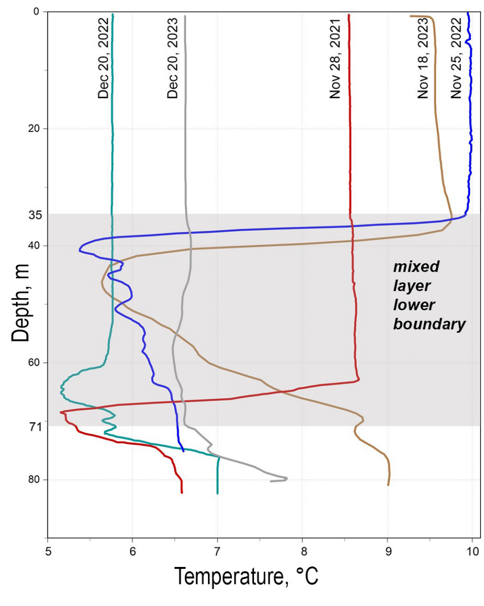

Figure 8. Temperature profiles in November–December, 2021–2023 at point 3.

5 Conclusions

The observed 20-years trends, such as increasing temperatures, stable salinity levels, and declining DO concentrations, highlight the complex relationship between natural processes and anthropogenic impacts within the Gdansk Deep. The increase in

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temperature within the deep layer, partly attributed to global ocean warming and more frequent warm summer inflows, has, in turn, partly led to a decrease in oxygen solubility. The steady decline in DO levels, despite relatively stable salinity, implies that eutrophication and the associated oxygen consumption play a critical role in the worsening of near-bottom hypoxic conditions even despite intra-pycnocline oxygenating intrusions between MBIs.

The results emphasize the need for ongoing monitoring and further research to understand the long-term ecological impacts of these changes. The potential for deep convection and other processes to contribute to oxygen supply in the deep layers, as observed in the winter of 2023, provides a critical insight into the dynamics of the Gdansk Deep's ecosystem. This study underscores the importance of considering both seasonal and interannual variations when assessing the health and sustainability of marine environments like the Baltic Sea.

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