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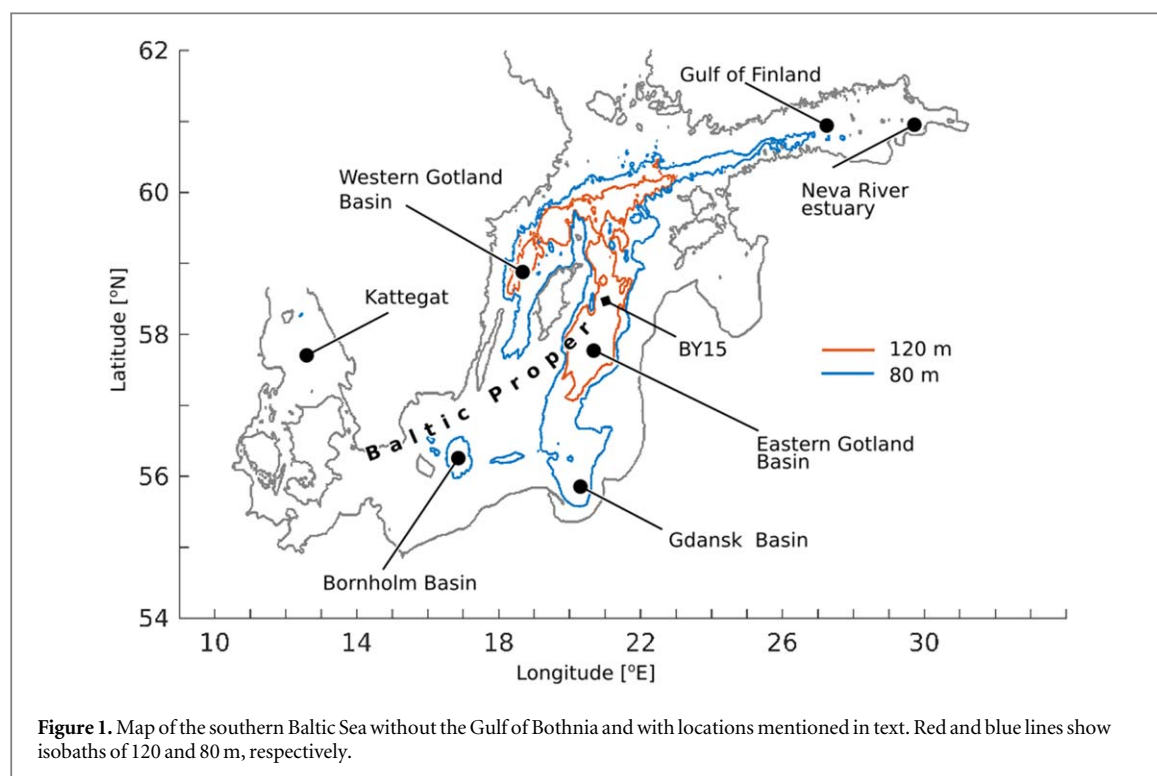
Abstract

Oxygen deficiency, in the form of hypoxia and anoxia, is a direct consequence of the eutrophication of the Baltic Sea. There is ongoing debate concerning the increasing extent of hypoxia. We analyse the integral metrics of hypoxia and anoxia: (1) temporal evolution of the hypoxic and anoxic area and volume, (2) the spatial distribution of the probabilities of hypoxia and anoxia occurrence in the Baltic Sea. The results are based on the state-of-the-art coupled physical and biogeochemical numerical model reanalysis data from Copernicus Marine Environment Monitoring Service for the period of 1993–2017. Statistical analysis showed that the variability of hypoxic and anoxic areas since the year 2000 represents stationary processes around their respective mean levels. From 2000 to 2017, the hypoxic area varies between 50000 and 80000 km² and the anoxic area varies between 10000 and 50000 km². Different methods and data sources indicate that the uncertainties of the estimates account for about 10000 km². We suggest that the loss of stationarity of the time series of the hypoxic area would be an indication of the regime change of hypoxia development in the Baltic Sea. Probability distribution maps of hypoxia and anoxia provide detailed information about the persistency of hypoxia and anoxia in different parts of the Baltic Sea. The probability of hypoxia exceeds 0.9 in the eastern and western Gotland basins and in the deep area of the Bornholm basin. The Gulf of Finland and the shallower areas that connect different deep basins of the Baltic Sea exhibit seasonal and episodic hypoxia. The 80 m and 120 m isobaths are the approximate bathymetry limits of hypoxia and anoxia occurrence, respectively. Our study supports previous knowledge that hypoxia development is controlled to a large degree by the depth of the permanent halocline.

1. Introduction

Oxygen concentration is an important indicator of eutrophication and the concurrent ecosystem shift or degradation of natural water bodies (Conley *et al* 2011, Carstensen *et al* 2014a). The Baltic Sea (figure 1) has been the subject of poor oxygen conditions for centuries, with an ecosystem that is mostly adapted to fluctuating oxygen content (Conley *et al* 2009). However, the increase of anthropogenic pressure in the 20th century has escalated the problem and driven the ecosystem to its tolerance limit (Gustafsson *et al* 2012, HELCOM, 2018).

Poor oxygen conditions are most commonly characterized by hypoxia, i.e., oxygen concentration below 2 mg l⁻¹ (e.g. Conley *et al* 2011, Carstensen *et al* 2014a, 2014b, Liblik *et al* 2018, Carstensen and Conley 2019, Sinkko *et al* 2019) or 2 ml l⁻¹ (e.g. Savchuk 2018, Meier *et al* 2019, Stoicescu *et al* 2019), and anoxia, i.e., absolute lack of oxygen, and the occurrence of hydrogen sulfide (Carstensen *et al* 2014b). In the Baltic Sea, hypoxia can occur in the open sea as well as coastal areas, lasting from a few days to several years. The area of hypoxic water at the bottom is the measure of the strength of hypoxia in the Baltic Sea. The geographical extent of the hypoxic area has a major impact on benthic organisms, biogeochemical processes and fisheries. The last period of oxic conditions in Baltic Sea bottoms was in the mid 1930s (Carstensen and Conley 2019). No sufficient measurements were available in the 1940s. Permanent hypoxia has been present in the open central Baltic Sea since the 1950s (Carstensen and Conley 2019). Seasonal hypoxia has been reported in several geographic



locations of the Baltic Sea (Reusch *et al* 2018), with a variable duration from spring to autumn (Conley *et al* 2011, Liblik *et al* 2018, Carstensen and Conley 2019). Episodic hypoxia can occur in shallow coastal areas with complex bottom topography (Conley *et al* 2011, Carstensen and Conley 2019, Virtanen *et al* 2019).

Since 1950, the hypoxic area has increased from 10000–20000 km² to 50000–80000 km² (Savchuk, 2018, Carstensen and Conley, 2019, Hansson *et al* 2019), but this increase has not been steady over the years. Actual values of hypoxic areas depend on whether an oxygen concentration of 2 mg l⁻¹ (Carstensen and Conley 2019) or 2 ml l⁻¹ (Savchuk, 2018, Hansson *et al* 2019) is used for the limit of hypoxia and how the data are processed. All data agree that there was a monotonic increase of hypoxic area from 1950 to 1965. In the period of 1965–1992, the hypoxic area was between 30 000–70 000 km². It is difficult to judge the presence of a distinct temporal pattern in the time series without statistical analysis. There was a clear minimum of the hypoxic area of 20000–25000 km² in 1993 (Savchuk, 2018, Carstensen and Conley 2019, Hansson *et al* 2019). At the end of the 1990s, hypoxic areas were restored to a level of 60000–70000 km² (Savchuk 2018, Carstensen and Conley 2019, Hansson *et al* 2019). Since the end of the 1990s, the hypoxic area has been on a level of 50000–80000 km².

Anoxia is present mainly in the deep central Baltic Sea. Interannual variations of the anoxic area closely follow interannual variations of the hypoxic area and do not exceed 40 000 km² in total during the period of 1970–2010 (Lehmann *et al* 2014). Major Baltic Inflows (Mohrholz 2018), large volume inflows of saline and oxygen rich water from the North Sea to the Baltic, interrupt anoxia in the deep Baltic Sea sub-basins, at least for a limited time period (Neumann *et al* 2017). Saraiva *et al* (2019) concluded that hypoxic and anoxic areas could change significantly, depending on nutrient load and climate change scenarios.

Temporal changes of oxygen concentration in a control volume of water are determined by the difference in cumulative sources and sinks acting on the volume (Fennel and Testa 2019). Atmosphere is the main external source of oxygen for the sea. Oxygen enters the sea via air-sea gas exchange. An excess of oxygen supply results in high oxygen concentration in the upper layer of the water column. The depth of oxygen penetration depends on the vertical stratification of the water column. Beneath the penetration depth of the air-to-sea oxygen flux, hypoxia can be reduced or enhanced by lateral transport of oxygen-rich or oxygen-deficient water and by biogeochemical processes of oxygen consumption and production.

In the Baltic Sea, persistent hypoxia can occur in areas where a permanent halocline is present (Väli *et al* 2013). Seasonal hypoxia may develop in areas with a seasonal pycnocline (Liblik *et al* 2018). Episodic events with hypoxia are related to specific local conditions: weak oxygen flux from the air, warm water and oxygen consumption prevailing over oxygen production (Virtanen *et al* 2019).

The aim of this study is to analyse the development of hypoxic and anoxic area and volume in the Baltic Sea from the end of the stagnation period in 1993 to 2017 using state-of-the-art statistical methods. At the end of the stagnation period, the hypoxic area was at its minimum extent. Since the 1990s, the number of available measurements has increased significantly compared to the preceding period. In addition to the statistical analysis of hypoxic area

development, we introduce the second metric, the hypoxic volume, to gain more confidence in our conclusions. The first objective of this study is to analyse the existence of the trends and statistical stationarity of the hypoxic and anoxic areas and volume development in the Baltic Sea. The second objective is to calculate the spatial distribution of the probabilities of hypoxia and anoxia occurrence in the Baltic proper (including the Gulf of Finland).

2. Materials and methods

2.1. Model description and setup

In this study, we use the physics and biochemistry reanalysis products (BALTICSEA_REANALYSIS_PHY_003_011, BALTICSEA_REANALYSIS_BIO_003_012) (www.marine.copernicus.eu) of the Baltic Monitoring Forecasting Centre of Copernicus Marine Environment Monitoring Service (BALMFC CMEMS). The reanalysis products are based on the Nemo-Nordic general circulation model (Pemberton *et al* 2017, Hordoir *et al* 2019) coupled with the SCOBI (Swedish Coastal and Ocean Biogeochemical) biogeochemistry model (Eilola *et al* 2009, Almroth-Rosell *et al* 2015). The SCOBI model system has been used in many applications, mainly coupled with the Rossby Centre Ocean model (e.g. Meier *et al* 2021).

The SCOBI biogeochemical model consists of 9 state variables: nitrate, ammonium, phosphate, three functional species of phytoplankton, zooplankton, detritus and oxygen (Eilola *et al* 2009). Oxygen dynamics are governed by air-sea exchange, primary production, respiration of plankton species and sediments, decomposition of detritus, denitrification of nitrate, and oxidation of ammonia by nitrifying bacteria. The surface oxygen flux is calculated using oxygen solubility, temperature and wind-dependent exchange rates. The model also takes into account supersaturation caused by injection of bubbles into sea water.

In the current application, the model system uses the Localized Singular Evolutive Interpolated Kalman (LSEIK, Nerger *et al* 2005) filter data assimilation method to combine simulation and the SST observations from OSISAF (<http://www.osi-saf.org/>) and *in situ* profiles of salinity and temperature from the ICES database (www.ices.dk), and nitrate, ammonium, phosphate and oxygen state variables from the Swedish Ocean Archive database (SHARK; <http://sharkweb.smhi.se>). The reanalysis has been produced using 72-hour cycling. This means that every 72 h all available observations were assimilated into the model, and then a 72-hour forecast was made.

The model domain consists of the North Sea and the Baltic Sea (Hordoir *et al* 2019), but we only use the reanalysis data for the Baltic Sea for the period 1993–2017. The horizontal resolution of the model is approximately 2 nautical miles. The thickness of 56 vertical layers varies from 3 m close to the surface, decreasing to 22 m at the bottom of the deepest part of the Norwegian trench. The numerical model simulation data covers the period of 1993–2017. The sea levels at the lateral boundary in the English Channel and northern edge of the North Sea have been derived from the coarse resolution storm-surge model NOAMOD (Dick *et al* 2001). Climatological mean values are prescribed for salinity and temperature at the open boundaries.

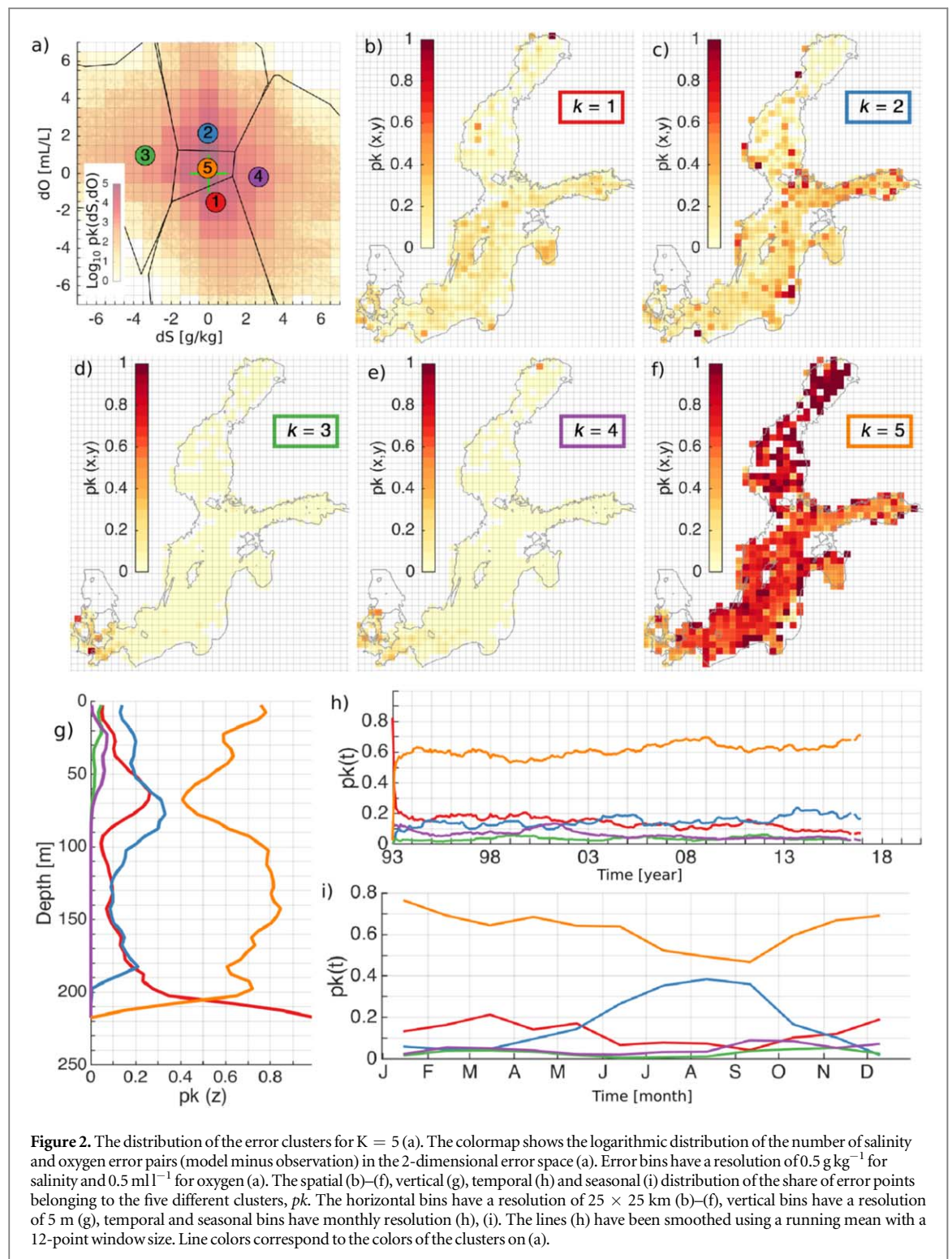
The river runoff is specified as daily means and nutrient loads as monthly means from the output of the HYdrological Predictions for the Environment (HYPE) model (Donnelly *et al* 2016). In total, 250 rivers located in the Baltic Sea are included (Hordoir *et al* 2019).

The meteorological forcing with a 22 km resolution is from HIRLAM (High-Resolution Limited Area Model), from project Euro4M (Dahlgren *et al* 2016, Landelius *et al* 2016), and covers the period 1993–2011. From 2012 to 2017, the meteorological forcing is from the UERRA reanalysis product (European Regional analysis) with an 11 km resolution. The bias correction of 0.8 was implemented for the precipitation from UERRA. Spatial maps of a monthly climatology are used for the atmospheric deposition of biogeochemical substances.

2.2. Model quality assessment using K-means clustering algorithm

We apply a method of clustering of the bivariate model errors that provides information on the accuracy of the model in general. The clustering is done using the K-means algorithm of unsupervised machine learning (Jain 2010). The method is originally described by Raudsepp and Maljutenko (2021). The first step of the method is the formation of a two-dimensional error space of two simultaneously measured parameters. Errors are calculated as the differences between model values and the measurements. The second step is the selection of the number of clusters. The third step is to perform a K-means clustering of the 2-dimensional errors. The clustering is applied to the normalized errors. Normalization is done for each variable separately using corresponding standard deviations of the errors. The fourth step is calculation of statistical metrics of non-normalized clustered errors. The fifth step is the analysis of spatio-temporal distributions of the errors belonging to different clusters.

We form a 2-dimensional error space of salinity and dissolved oxygen (figure 2(a)) as representatives of physical and biogeochemical models of the coupled model system. We use salinity and oxygen measurements



for the Baltic Sea from the EMODnet Chemistry database (Giorgetti *et al* 2020). In total, we have 651 565 simultaneous salinity and oxygen error pairs. Five clusters are selected using the Elbow cluster selection criteria (Yuan and Yang 2019, Bholowalia and Kumar 2014) after testing a different number of clusters. The outcome of the K-means clustering is shown on figure 2 and the metrics are presented in table 1.

2.3. Statistical methods for the validation

In order to assess the uncertainty of the anoxic and hypoxic areas, we have extracted oxygen profiles from the reanalysis and compared them with the *in situ* measurements at the Gotland Deep monitoring station (BY15, figure 1). We have used simulated and measured water temperature and salinity profiles for calculating water density profiles at station BY15. A direct comparison was made for density, as the latter characterizes vertical

Table 1. Statistics of the different error clusters shown in figure 2(a). BIAS is the mean of the errors in each cluster, i.e., coordinates of the centroids in figure 2(a). STD is the standard deviation of the errors in each cluster. RMSD is the root-mean-square deviation of the errors in each cluster. The correlation coefficients are calculated between modeled and measured values of the corresponding cluster.

k	BIAS		STD		RMSD		R	
	S [g kg ⁻¹]	DO [ml l ⁻¹]	S [g kg ⁻¹]	DO [ml l ⁻¹]	S [g kg ⁻¹]	DO [ml l ⁻¹]	S	DO
1	0.37	-1.54	0.61	0.95	0.72	1.81	0.99	0.93
2	-0.03	2.14	0.56	0.95	0.56	2.35	0.99	0.91
3	-3.38	0.95	1.78	1.25	3.82	1.57	0.95	0.76
4	2.67	-0.18	1.19	1.61	2.92	1.62	0.98	0.72
5	-0.06	0.28	0.40	0.47	0.40	0.55	0.99	0.98

stratification rather than temperature and salinity alone. The parameters used in this study are calculated from daily mean oxygen concentration, temperature and salinity fields.

Taylor diagrams (Taylor 2001) were prepared for the depth of selected oxygen isolines and isopycnals. The depths of oxygen and density isolines have been calculated as the first occurrence of the corresponding isoline, starting from the surface. For the Taylor diagram, common statistics, such as the Pearson correlation coefficient (r) and standard deviation (STD), are calculated. To plot multiple standard deviations on a common Taylor diagram, STDs of the simulated isoline depth have been normalized to the corresponding STD of the observed isoline depth. The data are not taken into account if either simulated or measured depth of an isoline is missing. Comparison of the simulated and the measured depths of oxygen isolines enables better assessment of the model performance than comparison of oxygen concentrations at fixed depths, as far as hypoxic and anoxic areas are concerned. Vertical stratification of the water column has a significant role in the development and the geographical extent of hypoxia (Fennel and Testa 2019).

2.4. Statistical methods for the analysis

The grid cell has been defined as anoxic or hypoxic if the concentration of oxygen in the water column is equal to 0 or less than 2 ml l⁻¹, respectively. Total area/volume of hypoxic or anoxic water was calculated as the sum of the area/volume of the grid cells where the anoxic or hypoxic water mass was present. A method for the calculation of hypoxic and anoxia area and volume from the measurements is described by Hansson *et al* (2019). We would like to note that model reanalysis data have daily resolution over the whole modeling period, while the measurements are collected in autumn.

The probability of anoxia or hypoxia occurrence is defined as the ratio of the number of days when anoxia or hypoxia was present at the grid cell to the total number of days during the period under consideration.

The hypsographic curve for the Baltic proper (including the Gulf of Finland) was calculated from the Baltic Sea Bathymetry Database (BSHC 2013) as a function of cumulative area over the given depth.

The temporal dynamics of area and volume below the defined oxygen level have been studied by means of statistical tests. The goal of the statistical tests is to test whether the 0-hypothesis, which is designed to reject the statement, can be rejected with a 95% confidence level, otherwise the statement can be accepted. The Mann-Kendall (MK) test (Mann 1945, Kendall 1975, Wang *et al* 2020) was performed to determine if monotonic increase or decrease exists in the time series of areas and volumes. The calculated Z test statistic of the MK test shows the sign and strength of the trend tendency. Linear trends have been estimated as slope parameters using the least square fit for the straight line, and statistical significance is calculated according to (Draper and Smith 1998).

The unit root Dickey-Fuller (DF) test has been performed to determine the stationarity of the time series (Dickey and Fuller 1979). For this, we test whether unitroot (stationarity) with a) drift and with b) drift and deterministic trend are present in the time series of oxygen area and volume. Values of the DF test τ statistic below τ_{crit} allow us to reject the 0-hypothesis, meaning that the time series represents a stationary process. Therefore, τ statistic can be interpreted as the strength of the stationarity of the time series.

3. Results

3.1. Overall model quality

62% of comparison points show a good match between the model and measurements (figure 2(a), table 1). The model performs well for the whole Baltic Sea and over the simulation period (figures 2(f), (h)). A somewhat reduced performance is geographically in the Gulf of Finland, Gulf of Riga and at the Danish straits (figures 2(b)–(e)), vertically within the redoxcline and at the bottom of the Gotland Deep (figure 2(g)), and seasonally during summer

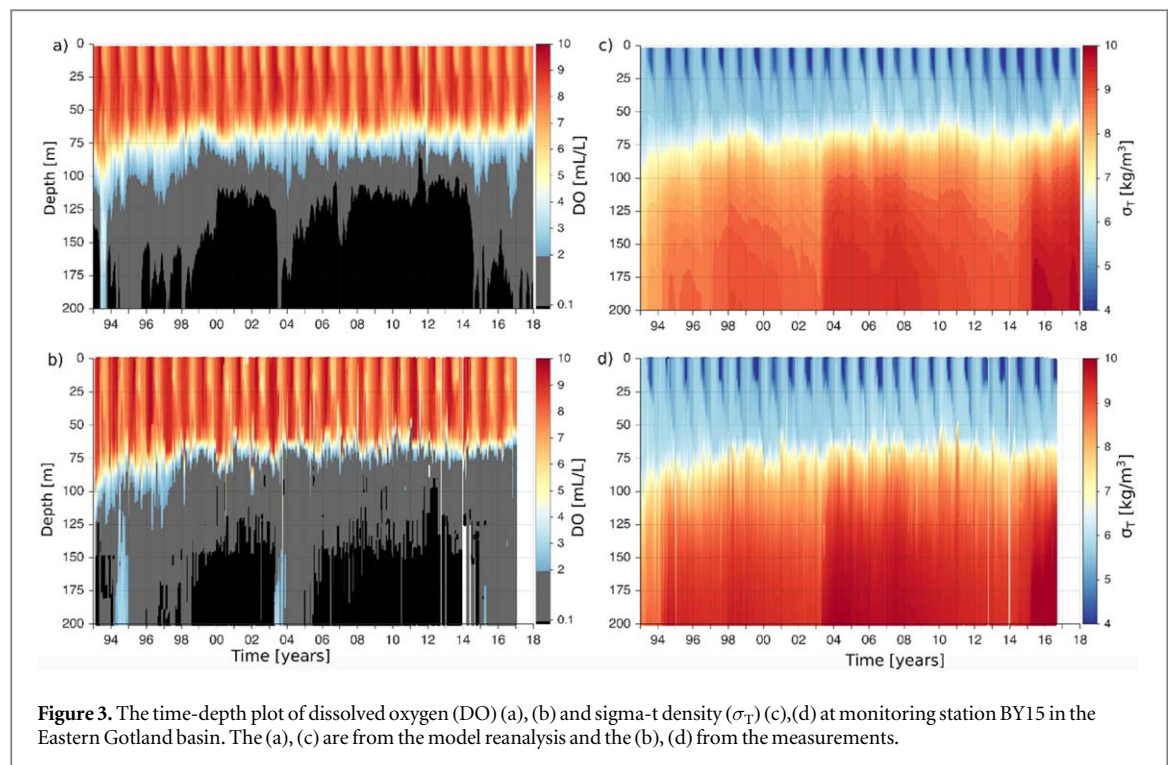


Table 2. The biases of the depth of oxygen and density isolines. The biases are calculated as corresponding model values minus measured values.

DO [ml l^{-1}]	bias [m]	σ_T [kg m^{-3}]	bias [m]
0.1	−13	5	−4
1	9	6	−4
2	11	7	−4
3	4	8	−3
4	3	9	3
5	2		
6	1		
7	0		
8	0		

(figure 2(i)). In the Gulf of Finland, the oxygen concentrations are partly overestimated, while salinity is well reproduced (figure 2(c)). In the Gulf of Riga, oxygen concentrations are underestimated and salinity is well reproduced (figure 2(b)). At the Danish straits, the situation is completely different compared to the rest of the Baltic Sea. The model either underestimates salinity (figure 2(d)), overestimates salinity (figure 2(e)) or reproduces it correctly (figure 2(f)) there. The oxygen concentrations there are well reproduced due to the shallowness of the area. In the redoxcline, i.e., in the depth range of 60–90 m (figure 3), we observe a situation of underestimated oxygen concentration with a peak share of model errors at a depth of 70 meters, and of overestimated oxygen concentration with a peak share of model errors at a depth of 80 meters (figure 2(g)). This type of vertical distribution of errors shows that the redoxcline is wider in the model than in the measurements. Seasonally, a higher share of overestimated oxygen concentration in summer than the rest of the year (figure 2(i)) accounts partly for the errors in the Gulf of Finland (figure 2(c)). The spatial distribution of bottom salinity and oxygen errors for different clusters shows that, although the model and data match is predominantly good, the share of overestimated oxygen concentration errors is still significant (figure A1).

3.2. Model validation in the Gotland Deep

Oxygen and density profiles, measured at the monitoring station BY15 in the eastern Gotland Basin and extracted from the model reanalysis, are compared to assess the model performance in the central Baltic proper (figure 3). Redoxcline and pycnocline are centered at a depth of about 75 m in the measurements and the model

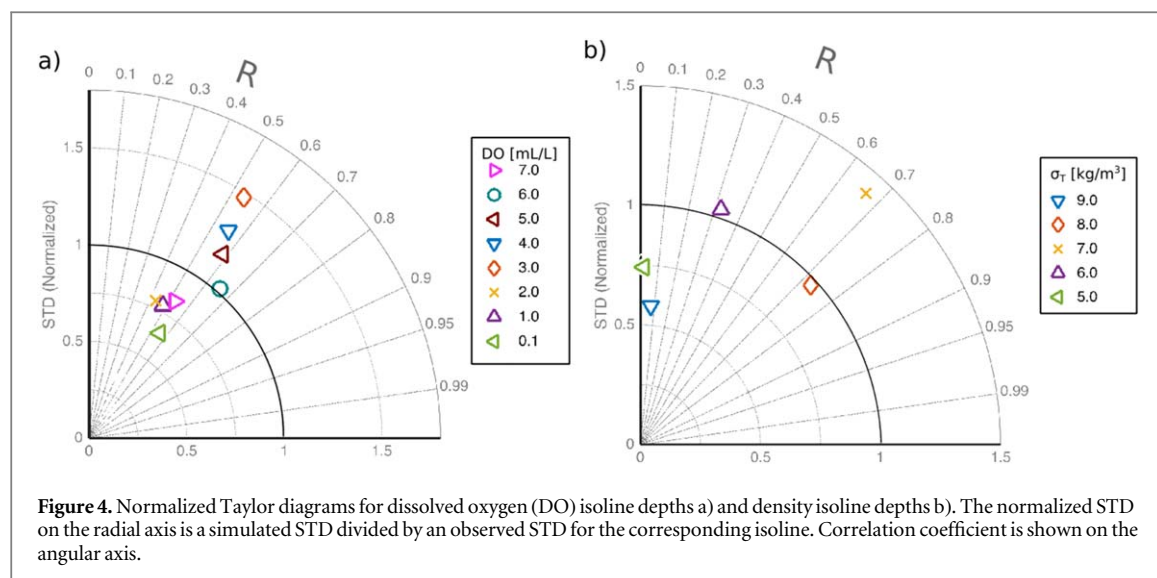


Table 3. Pearson correlation coefficients between different levels of oxygen volumes (upper triangle, red) and areas (lower triangle, blue).

		Volume correlation coefficients			
		Oxy, mL/L	0	1.43	2
Area correlation coefficients	0	1	0.81	0.72	0.53
	1.43	0.82	1	0.99	0.85
	2	0.75	0.98	1	0.91
	4	0.50	0.69	0.76	1

alike. The measured redoxcline is shallower while pycnocline is deeper than in the model, but the mean differences do not exceed 4 meters (table 2) and other metrics are satisfactory (figure 4). The hypoxic water layer extends to about 10 meters shallower in the measurements than in the model, i.e., the model underestimates hypoxic layer thickness. Instead, anoxic water layer thickness is overestimated in the model.

3.3. Temporal evolution of the hypoxic and anoxic area and volume

Time series of anoxic and hypoxic water areas and volumes for the Baltic Sea were calculated for the period of 1993–2017 from the model (figure 5). For comparison, we calculated the hypoxic area and volume corresponding to the hypoxia threshold of 1.43 ml l⁻¹ (stringent hypoxia) and 4 ml l⁻¹ (loose hypoxia). As expected, the area and volume are smaller in the case of stringent hypoxia than in the case of hypoxia, and the area and volume are larger in the case of loose hypoxia than in the case of hypoxia. However, no differences are seen in the temporal dynamics (figure 5, table 3). Seasonal changes in the area and volume of loose hypoxia, with a minimum in early spring and a maximum in early winter, are superimposed to long-term changes. Anoxic water area and volume changes correlate well with the hypoxic water area and volume changes, except in the case of loose hypoxia (table 3). A relatively low correlation coefficient of the oxygen isolines between 4 ml l⁻¹ and 0 ml l⁻¹ shows that the variability of the upper redoxcline and anoxic water below the redoxcline are weakly coupled.

As can be expected from the model and data comparison of the depth of oxygen concentration isoline of 2 ml l⁻¹ (table 2), the hypoxic area calculated from the model is about 10 000 km² smaller than calculated from the measurements (figure 5). The same is true for the anoxic area, although the depth of the anoxia isoline was smaller in the model than in the measurements at the Gotland deep station (figure 5, table 2).

In general, there are two different regimes in the evolution of the hypoxic area and volume in the Baltic Sea (figure 5). The first period, from 1993 to 1999, shows a steady increase of the hypoxic area and volume with a rate of 5000 km²/year and 200 km³/year, respectively (table 4). The trends of anoxic area and volume are smaller, accounting for 1 400 km²/year and 30 km³/year, respectively. From 2000 to 2017, the hypoxic area varies between 50000 and 80000 km². The anoxic area varies between 10000 and 50000 km² with an apparent long-term periodicity of 10 years. The periodicity is related to large volume inflows of North Sea water into the Baltic

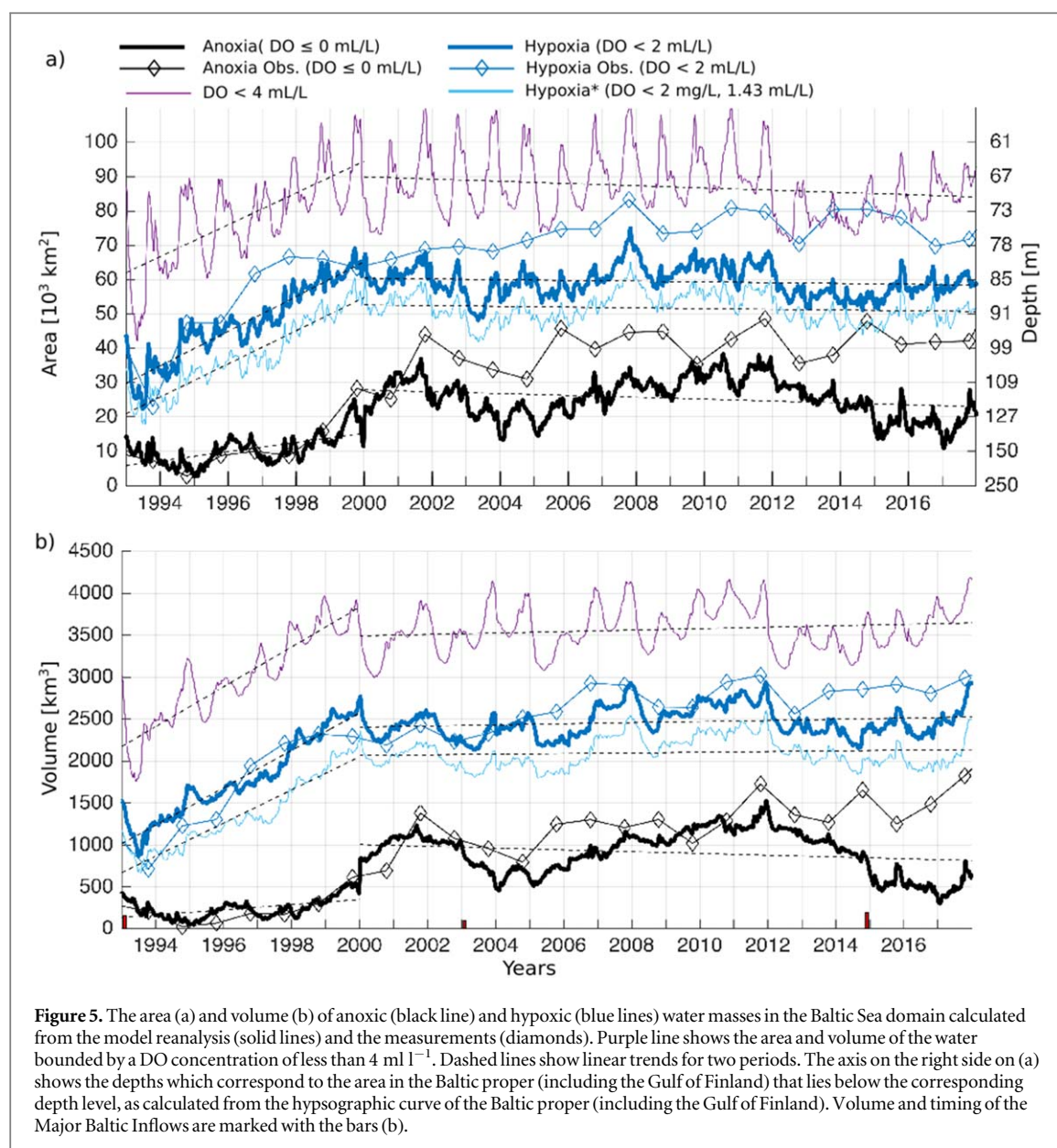


Table 4. Trend analysis of oxygen volume and area time series. H shows which hypothesis is accepted according to the Mann-Kendal test. p-value shows the probability by which the 0-hypothesis is true with the corresponding Z-statistic.

Area trends [1000 km ² /y]								
Oxy, mL/L	p1 trend	MK H	p-value	MK Z-stat	p2 trend	MK H	p-value	MK Z-stat
0	1.36	1	<10 ⁻⁴	0.41	-0.27	1	<10 ⁻⁴	-0.15
1.43	4.83	1	<10 ⁻⁴	0.79	-0.11	1	<10 ⁻⁴	-0.09
2	5.05	1	<10 ⁻⁴	0.78	-0.11	1	<10 ⁻⁴	-0.08
4	4.64	1	<10 ⁻⁴	0.49	-0.33	1	<10 ⁻⁴	-0.10
Volume trends [km ³ /y]								
Oxy, mL/L	p1 trend	MK H	p-value	MK Z-stat	p2 trend	MK H	p-value	MK Z-stat
0	30.56	1	<10 ⁻⁴	0.34	-10.55	1	<10 ⁻⁴	-0.09
1.43	197.31	1	<10 ⁻⁴	0.84	3.98	1	<10 ⁻⁴	0.06
2	222.97	1	<10 ⁻⁴	0.87	6.72	1	<10 ⁻⁴	0.12
4	237.44	1	<10 ⁻⁴	0.74	8.67	1	<10 ⁻⁴	0.11

Sea, consisting of Major Baltic Inflows in 2003 and 2014 (figure 5(b)). During the second period, 2000–2017, we have a small negative trend in the area and volume of the anoxic water (figure 5; table 4). Somewhat surprisingly, the areas of hypoxic waters have small negative trends, while the volumes have small positive trends (table 4).

The measurements confirm the presence of an increasing trend of hypoxic and anoxic areas and volumes during the period 1993–1999. During the second period, positive trends in the areas and volumes of hypoxic and anoxic water of the Baltic Sea are small.

We performed statistical tests to determine the existence of monotonic trends and stationarity of the time series for two periods. According to the MK test, there are statistically significant trends in all time series during both periods (table 4). The Z statistic of the MK test shows the strength of the trend. Positive trends in the time series of the hypoxic and anoxic area and volume are relatively strong during the first period. Negative trends in the area and positive trends in the volume of hypoxic water are rather weak during the second period (table 4). The DF tests show somewhat scattered results (table 5). The time series of areas of hypoxic and anoxic water show stationarity with a drift in the second period. The DF test with drift and trend shows stationarity of anoxia, stringent hypoxia and hypoxia during both periods. Although the stationarity test fails for loose hypoxia, the p-value is close to the acceptance level, and τ -statistic is relatively low. The DF tests of the volume time series show stationarity only for hypoxia around the trend in the first period, while not showing stationarity for anoxia. In the second period, the test shows no stationarity of hypoxia development (table 5). Although the trends can be calculated, no meaningful statistical test can be performed for measured hypoxia and anoxia area and volume, because there is limited data, only one value per year.

3.4. Probability of hypoxia and anoxia occurrence

For the characterization of hypoxia and anoxia, we use the probability of hypoxia and anoxia occurrence, which enables us to integrate the spatio-temporal variations of hypoxic and anoxic areas in the Baltic Sea (figure 6). The regions with a hypoxia and anoxia probability of 0.25 could be considered as proxy for seasonal hypoxia and anoxia, i.e., 3 months out of 12 could have hypoxia and anoxia. In addition, these areas could potentially be the areas prone to long-term hypoxia or anoxia. The period of 1993–1999 is characterized by the development of permanent hypoxia in the parts of the Baltic Sea that have a greater depth than 80 m (figures 6(a), (c)). Moreover, from the hypsographic curve of the Baltic Sea (figure 5(a)), we can say that the 80 m isobath represents the characteristic depth of the upper bound of the hypoxic area. From a physical point of view, the Baltic proper has a persistent and strong density stratification with a pycnocline at a depth of about 60–80 m (figure 3). Thus, with some concessions, we use the 80 m depth as a robust characteristic depth that binds the depths of hypoxic water and the pycnocline in the central Baltic Sea. However, in the Bornholm Basin, persistent hypoxia with an episodic increase of oxygen concentrations occurs in the areas shallower than 80 m (figure 6). An opposite pattern with a persistent hypoxia deeper than 80 m is characteristic of the Gdansk Basin. Seasonal or episodic hypoxia occurs in the transition area between Gdansk and Eastern Gotland basins. Among shallow areas, the Neva River estuary is prone to frequent hypoxia and even anoxia (figure 6). During the period between 2000–2017, the probability of hypoxia has increased in the areas deeper than 80 m (figure 6). Geographically, the area with increased hypoxia probability has spread southward in the Eastern and Western Gotland basins. In addition, the hypoxic area has increased at the entrance to the Gulf of Finland and in the western part of the gulf.

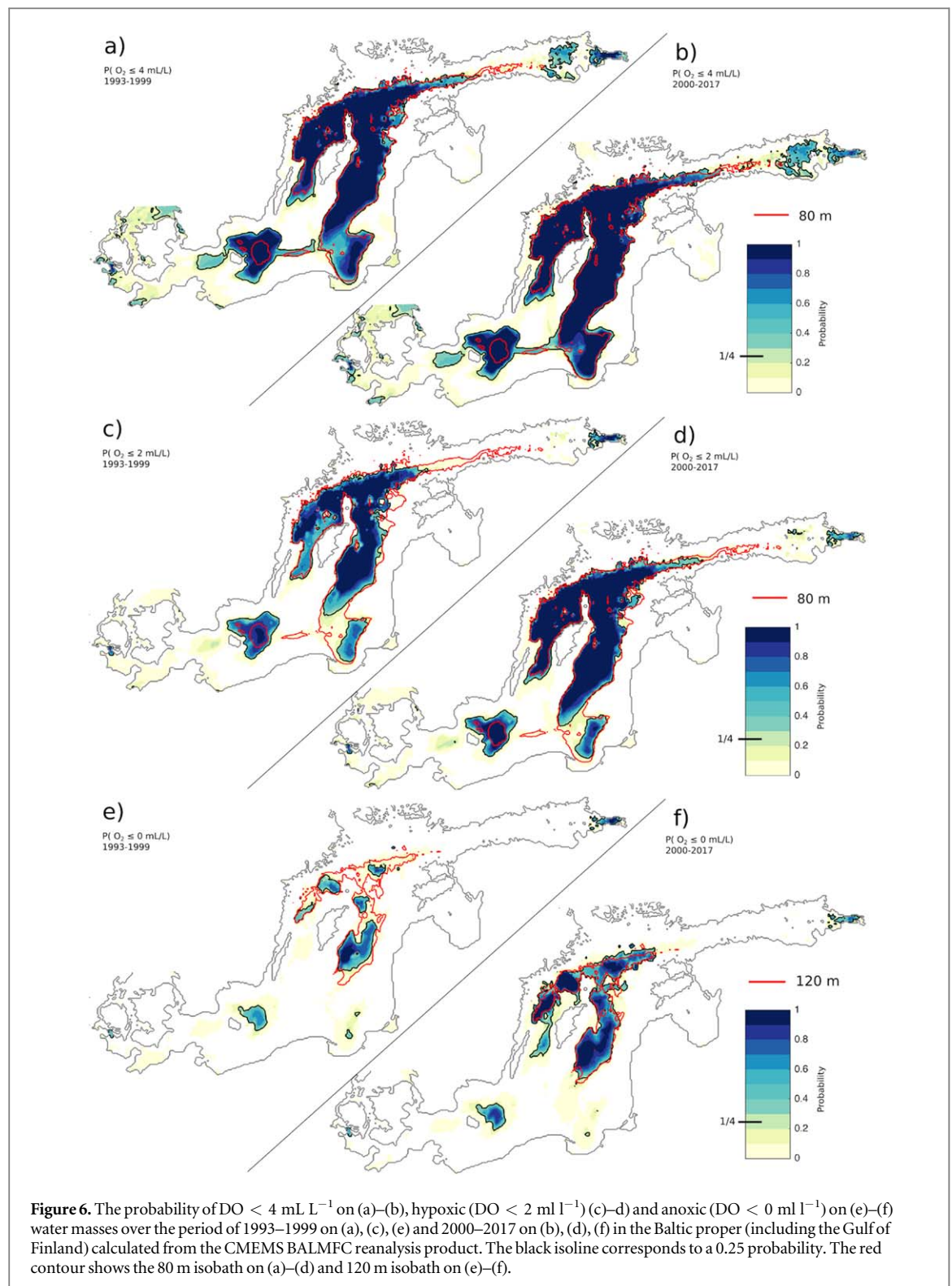
There were no permanent anoxic regions in the Baltic Sea during the time period of 1993–1999, except in the deepest local areas of the Eastern Gotland Basin and Northern Baltic proper (figure 6(e)). Anoxic area has increased geographically and probability-wise from 1993–1999 to 2000–2017 (figure 6). However, in the southern Baltic Sea, the areas with an anoxia probability of less than 0.25 during 1993–1999 have turned into permanently anoxic areas during 2000–2017. Rather than indicating seasonal and episodic anoxia, the changes in probability from lower values during the first period to higher values during the second period show gradual development of anoxia. In the Bornholm Basin and Gdansk Basin, the anoxic areas with lower probability than 0.25 could point to areas with seasonal and episodic anoxia. A 120 m isobath captures the area with anoxia probability exceeding the value of 0.25 relatively well (figure 6(f)).

Loose hypoxia covers areas with episodic, seasonal and permanent hypoxia. It can be considered as the upper limit of the occurrence of hypoxia and anoxia (figure 6). This statement is justified by comparing the geographical areas where loose hypoxia has a probability that exceeds 0.25. These geographical areas have not spread remarkably from the first to the second period. In the southern Baltic Sea, the area of loose hypoxia with an occurrence probability of less than 0.25 has decreased, yet it has increased in the Gulf of Finland.

In order to summarize the development of hypoxia and anoxia in the Baltic Sea and its relation to vertical stratification, we have drawn mean profiles of oxygen concentration and water density for the first and the second period at the location of the monitoring station BY15 (figure 7). In the upper 50 m layer, water density and oxygen concentration have not changed significantly. The pycnocline and redoxcline have gradually lifted upward, starting at a depth of 60 m. For instance, the depth of the 8 kg m^{-3} density has decreased from 100 to 85 m, and the depth of the 2 ml l^{-1} oxygen concentration has decreased from 110 to 90 m. Below the pycnocline, the water density has increased. Below the redoxcline, the oxygen concentration has decreased. The water has become anoxic below a depth of 120 m.

Table 5. Stationarity test for oxygen area and volume time series. H shows which hypothesis is accepted, p-value shows the probability by which the 0-hypothesis is true with the corresponding τ -statistic.

Area	Drift						Drift + Trend					
	p1			p2			p1			p2		
	H	p-value	DF τ -stat	H	p-value	DF τ -stat	H	p-value	τ -stat	H	p-value	DF τ -stat
Oxy, mL/L												
0	0	0.14	−2.42	1	0.004	−3.79	1	0.015	−3.85	1	0.009	−3.99
1.43	0	0.83	−0.76	1	$<10^{-3}$	−4.91	1	$<10^{-3}$	−5.14	1	$<10^{-3}$	−4.90
2	0	0.79	−0.88	1	$<10^{-3}$	−4.78	1	$<10^{-3}$	−4.94	1	$<10^{-3}$	−4.78
4	0	0.35	−1.89	1	0.022	−3.17	0	0.085	−3.20	0	0.084	−3.20
Volume												
	Drift			Drift + Trend			p1			p2		
	p1	p-value	DF τ -stat	p2	p-value	DF τ -stat	H	p-value	DF τ -stat	H	p-value	DF τ -stat
Oxy, mL/L												
0	0	0.87	−0.57	0	0.44	−1.68	0	0.63	−1.93	0	0.66	−1.87
1.43	0	1.00	1.01	0	0.13	−2.43	1	0.04	−3.55	0	0.30	−2.59
2	0	0.99	0.76	0	0.15	−2.37	1	0.01	−3.95	0	0.25	−2.68
4	0	0.91	−0.37	0	0.39	−1.79	1	0.02	−3.73	0	0.61	−1.96



4. Discussion

In the case of modeling, it can be argued that model-based estimates have large uncertainties due to the deficiencies of the model in describing physical and biogeochemical processes, initial fields, external inputs and forcing. In the case of measurement-based estimates, we once again face the issue of large uncertainties, as measurements lack spatial and temporal resolution and were not made simultaneously, and any kind of interpolation procedure introduces uncertainties in the estimates. Therefore, in this analysis, we use reanalysis fields, which integrate both model simulation ability and existing measurements. In this study, we used an advanced numerical model system which has been proven to provide acceptable results in many applications.

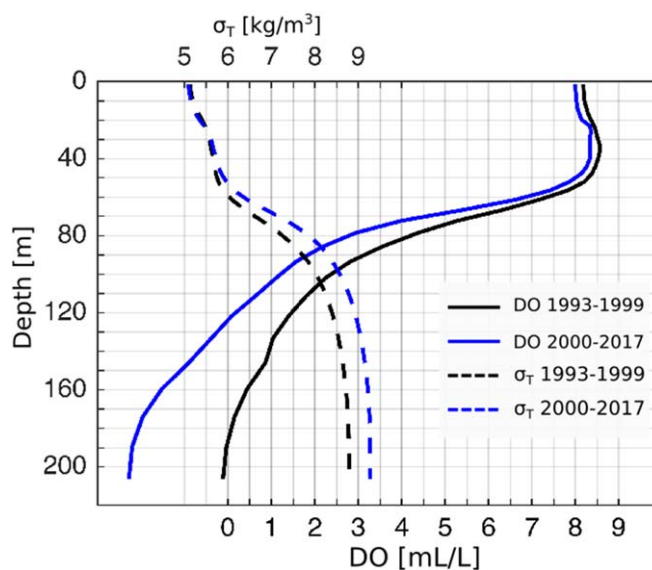


Figure 7. The vertical profiles of averaged dissolved oxygen (DO) and water density (σ_T) over the period of 1993–1999 and 2000–2017 at BY15 calculated from the model reanalysis product. Concentrations of hydrogen sulphide are presented as negative oxygen.

Using the data assimilation technique is definitely an advantage, as it improves the quality of the simulation product. We performed extensive validation of the model oxygen, salinity and density fields to assure the credibility of our results. The discrepancies between reanalysis and observations are mainly due to the imperfect data assimilation method and because the model cannot perfectly resolve the oxygen dynamic at the deeper layers.

Indeed, the current reanalysis data may underestimate the extent of hypoxic area, as indicated by the overestimated depth of the oxygen concentration isoline of 2 ml l^{-1} (table 2) and comparison with the estimates based on measurement data (figure 5). Therefore, we used several thresholds for hypoxia, which enabled us to define the limits of uncertainties and indicate a potential evolution of oxygen deficiency in the Baltic Sea. These thresholds include the range of low oxygen concentrations that have a negative impact on marine life. Animals display a wide tolerance span to oxygen conditions, but the underlying understanding is that lethal and sublethal effects along with stress negatively affect the functionality of marine ecosystems and reduce their resistance to environmental and anthropogenic disturbance (Carstensen *et al* 2014a, Laffoley and Baxter 2019). In the Baltic Sea, fisheries are of high economic importance to the surrounding countries. It has been noted that low oxygen concentrations affect cod reproductive volume, an indicator showing the water volume suitable for cod spawning, which is directly linked to the viability of cod stocks in the Baltic Sea (Carstensen *et al* 2014b, Raudsepp *et al* 2019a). In addition, hypoxia hinders the biogeochemical feedback loops and biomass production carried out by benthic fauna (Carstensen *et al* 2014a). The lack of oxygen at the seabed results in potential dead zones that are uninhabitable by most organisms. With that, the Baltic Sea sediments become an active ammonium and phosphorus source as soon as the sediments turn anoxic (Carstensen *et al* 2014b). These anoxia-related changes counteract nutrient mitigation measures and fuel the eutrophication process (Carstensen *et al* 2014b). The reduction in water quality, in turn, reduces the value of the Baltic Sea for recreation and other uses of marine resources.

In the development of the hypoxic and anoxic areas and volumes of the Baltic Sea from 1993 to 2017, two dynamically different periods are present. The first period, from 1993 to 1999, indicates a continuous increase of the areas and volumes of hypoxic water, no matter which threshold of oxygen concentration we use for the limit of the hypoxic water (figure 5). The MK test showed that increasing trends, which are not necessarily linear, are statistically significant. The DF test confirmed the existence of linear trends in most cases considered. In addition, the test showed that the area and volume changes superimposed to the trends represented the stationary process (tables 4 and 5). Indeed, the time series of hypoxic and anoxic areas and volumes are not perfectly homogenous and the natural variability is quite high.

We obtain from the model and measurements that the hypoxic area increased from 20000 km^2 in 1993 to about 60000 km^2 in 1999 (figure 5(a)). From 2000 until 2017, the area and volume of anoxic and hypoxic waters varied in the range of $10000\text{--}50000 \text{ km}^2$ and $50000\text{--}80000 \text{ km}^2$ and $500\text{--}2000 \text{ km}^3$ and $2000\text{--}3000 \text{ km}^3$, respectively, (figure 5). Independent estimates based on the measurement data have given variations of the

hypoxic area of the Baltic Sea in the range of 50000–80000 km² for the same period (Savchuk 2018, Carstensen and Conley 2019, Hansson *et al* 2019). The seasonal minimum of the loose hypoxic area drops to the value of 80000 km² almost every year (figure 5(a)), which can be assumed as the limit of the area ventilated by seasonal oxygen supply. Hence, we can robustly estimate that the hypoxic area is bounded by the 80 000 km² level during the period of 2000–2017.

The 80 m isobath can be considered as the characteristic depth of the hypoxic area in the Baltic proper (including the Gulf of Finland) (figures 5–7). From a physical point of view, the Baltic proper (including the Gulf of Finland) has a persistent strong density stratification with a halocline at a depth of about 60–80 m (Matthäus 1984, Väli *et al* 2013). The halocline is shallower than 80 m in depth in the Bornholm Basin and deeper in the Gdansk Basin (e.g. Väli *et al* 2013), which explains the hypoxia probability distribution there (figure 6). In the Gulf of Finland, seasonal salt wedge dynamics play a significant role in changing stratification (Maljutenko and Raudsepp 2019). Therefore, the probability of hypoxia occurrence is less than 0.5 there (figure 6).

After the Major Baltic Inflow in 1993, the hypoxic area and volume started to increase in the Baltic Sea (figure 5; Savchuk 2018, Carstensen and Conley 2019, Hansson *et al* 2019). A progressive geographical spreading of hypoxic and anoxic waters in time was described by the decrease of hypoxia probability distribution from deeper to shallower areas during the first period (figures 6(c),(e)). During the second period, the hypoxic and anoxic areas were on a relatively steady level (figure 5(a)). In that instance, high probability corresponds to persistent hypoxia and low probability to episodic hypoxia (figures 6(d),(f)). Visual comparison of our results and annual spatial maps of hypoxia and anoxia by Hansson *et al* (2019) enables us to draw a robust conclusion. The areas with a probability higher than 0.25 represent persistent hypoxia and anoxia. The regions with a hypoxia probability below 0.25 are seasonally or episodically hypoxic.

So far, poor oxygen conditions in the deep basins of the Baltic Sea have been attributed to the absence of the Major Baltic Inflows and additional inflows that do not classify as Major Baltic Inflows due to their small volume (Neumann *et al* 2017). Recent studies have shown a rapid decline of the oxygen concentration and restoration of anoxia in the Gotland Basin after the Major Baltic Inflow in 2014 (Neumann *et al* 2017, Raudsepp *et al* 2018a). Input of total nitrogen and phosphorus has decreased over decades (Savchuk 2018). At the same time, the inorganic nitrogen pool has decreased, but the inorganic phosphorus pool has increased (Savchuk 2018, Kõuts *et al* 2021). Similar tendencies are true for total nitrogen and total phosphorus pools (Savchuk 2018). Therefore, we might need to consider local biogeochemistry as the other important factor directly affecting dissolved oxygen concentrations below the halocline. Meier *et al* (2018) explained the rapidly worsening oxygen conditions after 2015, with higher amounts of organic matter being transported to the deep layers where decomposition consumes the remaining oxygen fast. With worsening oxygen conditions, the role of sediments changes from nitrogen removal to nitrogen release as ammonium (Carstensen *et al* 2014b). Phosphorus, which is buried in the sediment in organic form or bound to iron oxides, is readily released to the water column upon the onset of anoxia (Carstensen *et al* 2014a). This, in turn, can sustain cyanobacterial summer blooms, creating a positive-feedback mechanism that maintains hypoxia (Vahtera *et al* 2007). Neither phytoplankton spring blooms nor cyanobacteria summer blooms have increased in the Baltic Sea since the second half of the 2000s (Raudsepp *et al* 2018b, 2019b).

The halocline depth or vertical stratification in general has an impact on the development of hypoxic areas in the Baltic Sea (Meier *et al* 2011, Väli *et al* 2013) as well as in many other natural water basins (e.g. Fennel and Testa 2019 for review). The coinciding uplift of the pycnocline and redoxcline in the Gotland Basin between the two periods provides evidence of a close relationship between physical and biochemical processes (figure 7). Physical processes affecting vertical stratification in different parts of the Baltic Sea include vertical mixing due to winds and heat exchange between air and sea, wind-driven circulation and spreading of river water on one side, and inflows of the North Sea water into the Baltic Sea and its spreading into the deep sub-basins on the other side (Reissmann *et al* 2009, Väli *et al* 2013). The Major Baltic Inflows bring in oxygenated water, which temporarily improves the conditions under the halocline, but in the long term, this increases stratification and reduces downward mixing of oxygen (Carstensen and Conley 2019). Since 1993, there has been a positive trend in salinity of about 0.025–0.05 g kg^{−1} per year below the depth of about 70 m, but not in the upper layer of 50 m (von Schuckmann *et al* 2019). This shows the strengthening of vertical stratification. Thus, we might expect a decrease of hypoxic layer thickness from above due to oxygen diffusion in the case of weaker vertical stratification and braking of saline water inflows to the Baltic Sea (Lessin *et al* 2014). In contrast, the hypoxic layer thickness can increase due to frequent transport of saline water from the Kattegat to the deeper layers of the Baltic Sea. The intensity of these processes is highly unpredictable in the future as well as unmanageable by anthropogenic action. Therefore, methods to stop the eutrophication of the Baltic Sea in terms of its poor

oxygen conditions caused by human intervention might not be implemented easily due to the superiority of natural processes.

5. Conclusions

The Baltic Sea is an eutrophic inland sea with multiple stressors, both natural and anthropogenic, affecting its state. The Baltic Sea eutrophication state is evaluated based on dissolved oxygen concentrations over the period of 1993–2017. We have used two metrics, area and volume, for the description of hypoxia and anoxia in the Baltic Sea. Both of these characteristics carry similar but not identical information about the temporal variations of hypoxia and anoxia.

After the stagnation period, which was terminated by the Major Baltic Inflow in 1993, hypoxia development has shown two regimes. The first period, from 1993 to 1999, represents a trend-stationary process of the increase of hypoxic area from 20000 km² to a level of about 60000 km². The second period, from 2000 to 2017, can be characterized as a stationary process with a variable hypoxic area between 50000 and 80000 km². The anoxic area varies between 10 000 and 50000 km². It is recognized that the records of hypoxic and anoxic areas are not perfectly homogenous and can vary due to natural factors. In the Gotland basin, the lower bound of the redoxcline has been uplifted from about a 100 m depth to an 80 m depth calculated as the averages for two periods. Stationarity of the time series means that the statistical properties of a system do not change over time. Therefore, by adding data from the following years, the loss of stationarity of the time series would be an indication of the future change of the hypoxia regime. In addition to natural variability of hypoxic and anoxic areas, about 10 000 km² of uncertainty is caused by different methods, either numerical models or data interpolation procedures, used for the estimation of the areas of hypoxic and anoxic water. We propose using a multi-model ensemble combined with the measurement data for reducing uncertainties in the estimation of the hypoxia area and volume of the Baltic Sea.

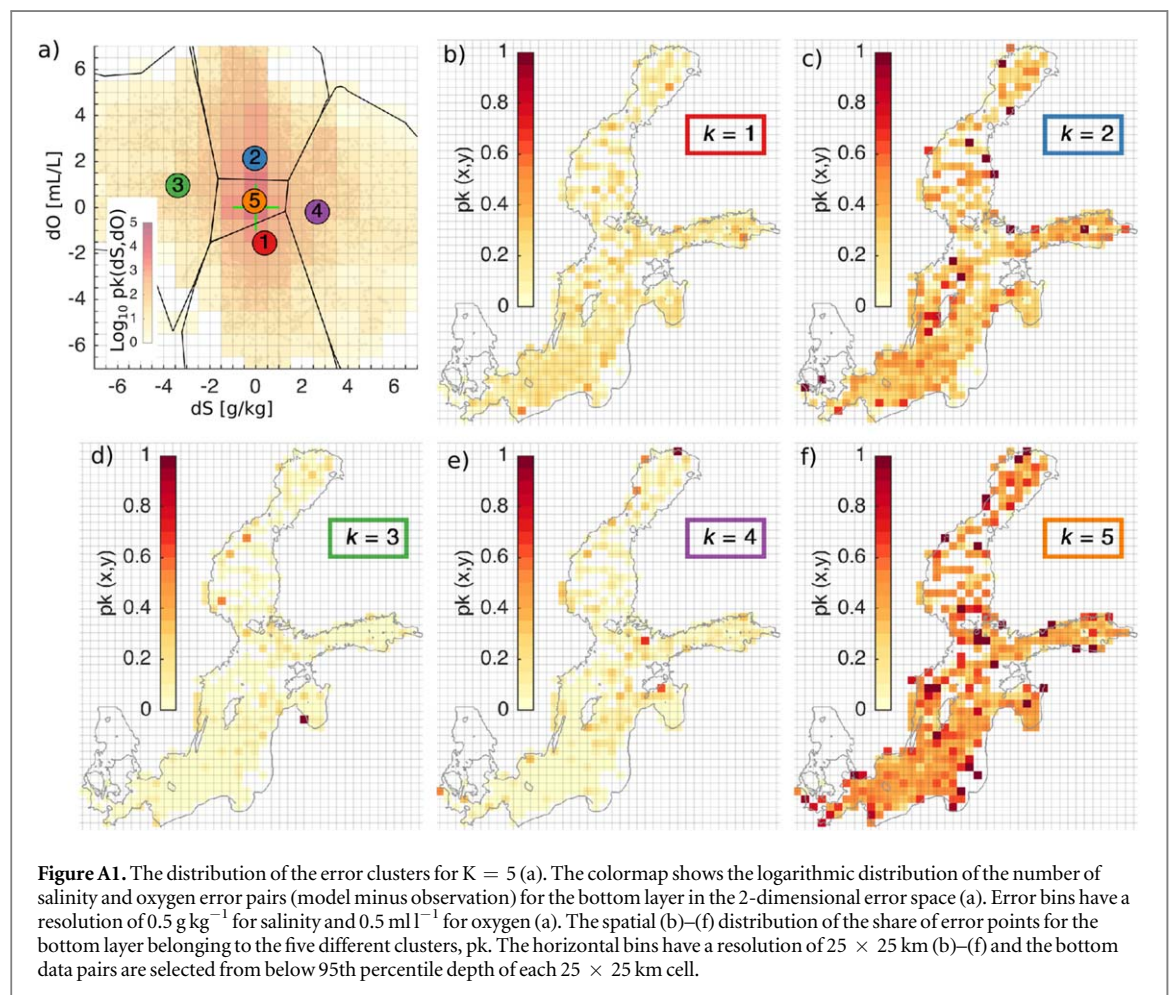
The measurements provide spatial and temporal snapshots of hypoxia coverage. Probability distribution maps of hypoxia occurrence integrate temporal variations of the hypoxia over a certain period into spatial maps. From the period 1993–1999 to 2000–2017 hypoxic and anoxic areas have expanded geographically in the Baltic Sea, but the probability distribution maps show the quantitative measure of this expansion. The southern areas of the eastern and western Gotland basin have become permanently hypoxic. In comparison, the expansion of the hypoxia towards the northeast, i.e., to the Gulf of Finland, has been moderate. The area at the entrance to the Gulf of Finland has turned from seasonal or episodic hypoxia into 50% hypoxic, while the area of seasonal or episodic hypoxia has spread eastward along the thalweg. The eastern Gulf of Finland as well as the connecting shallow area between the Gdansk and eastern Gotland basin are prone to seasonal and episodic hypoxia. Anoxia has become more persistent in the deep basins of the Baltic proper. Probability distribution maps may serve as identification of the areas which can be affected by hypoxia in relation to important ecosystem components, e.g., they allow to explain spatial distribution of marine fauna in response to their tolerance to frequent hypoxia and anoxia.

For following research, we hypothesize that hypoxia development is controlled by vertical stratification, which varies due to highly natural processes and is not prone to human interference. The hypoxic area can decrease with the weakening of stratification due to braking of large volume inflows to the Baltic Sea or increase due to strengthening of the stratification caused by frequent saline water inflows. Taking into consideration the current tendency of the development of hypoxic areas from 1993–1999 to 2000–2017, we suggest that persistent hypoxic areas may increase further in the Gulf of Finland and in the southeastern Baltic Sea where hypoxia is currently seasonal or episodic. The persistent anoxic area could increase to the limits of the hypoxic area in the case of favourable interaction of physical and biogeochemical processes.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Appendix



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