Causes of the extensive hypoxia in the Gulf of Riga in 2018

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Abstract. The Gulf of Riga is a relatively shallow bay connected to the deeper central Baltic Sea (Baltic Proper) via straits with sills. The decrease in the near-bottom oxygen levels from spring to autumn is a common feature in the gulf, but in 2018, extensive
10 hypoxia was observed. We analyzed temperature, salinity, oxygen, and nutrient data collected in 2018, along with historical data available from environmental databases. Meteorological and hydrological data from the study year were compared with their long-term means and variability. We suggest that pronounced oxygen depletion occurred in 2018 due to a distinct development of vertical stratification. Seasonal stratification developed early and was stronger in spring-summer 2018 than on average due to high heat flux and weak winds. Dominating north-easterly winds in early spring and summer supported the inflow of saltier waters from the Baltic
15 Proper that created an additional deep pycnocline restricting vertical transport between the near-bottom layer (NBL) and the water column above. The estimated oxygen consumption rate ~~at~~in the ~~sediment surface~~NBL in spring-summer 2018 was about 1.7 mmol $O_2\,m^{-2}\,h^{-1}$, which exceeded the oxygen input to the NBL due to advection and _vertical_ mixing. Such consumption rate leads to near-bottom hypoxia in all years when vertical mixing in autumn reaches the seabed later than on average according to the long-term (1979-2018) meteorological conditions. The observed increase in phosphate concentrations in the NBL in summer 2018 suggests a
20 significant sediment phosphorus release in hypoxic conditions counteracting the mitigation measures to combat eutrophication. Since climate change projections predict that meteorological conditions comparable to those in 2018 will occur more frequently ~~in the future~~, extensive hypoxia would be more common in the Gulf of Riga and other coastal basins with similar morphology and human-induced elevated input of nutrients.

1. Introduction

Coastal dead zones have expanded in the oceans since the 1960s, a phenomenon which is mostly caused by increased primary production as a result of eutrophication (Diaz and Rosenberg, 2008). Geographic settings such as openness of the basin and hydrographic conditions such as the strength and onset of stratification affect the magnitude of near-bottom hypoxia (Codiga et al., 2009; Liblik et al., 2020b; Murphy et al., 2011; Ukrainskii and Popov, 2009; Zhang et al., 2010)(Codiga et al., 2009; Liblik et al., 2020; Murphy et al., 2011; Ukrainskii and Popov, 2009; Zhang et al., 2010). Current and projected climate changes continue to affect the marine environment, e.g., increased temperature and strengthening of stratification in estuaries cause decreases in oxygen solubility and vertical mixing, respectively, which could lead to enhanced oxygen depletion of bottom waters (Bindoff et al., 2019).

The Baltic Sea is strongly influenced by eutrophication and changing climate conditions (Conley et al., 2009; Gustafsson et al., 2012; Kabel et al., 2012). The primary drivers behind eutrophication are excessive amounts of nutrients that enter the marine environment through rivers and the atmosphere (HELCOM, 2018b).(HELCOM, 2018b; Reusch et al., 2018). Hypoxic conditions have been found throughout the Baltic Sea as quasi-permanent, seasonal, or exceptional infrequent phenomena (Conley et al., 2007, 2011; Karlson et al., 2002)(Carstensen and Conley, 2019; Conley et al., 2007, 2011; Karlson et al., 2002). Hypoxia and anoxia have occurred in open water areas of the Baltic Proper below the halocline (~70-80 m) on an almost permanent basis since the 1950s (HELCOM, 2016; Karlson et al., 2002). Occasionally, oxygen conditions in this central basin are improved by Major Baltic Inflows (e.g., Matthäus and Franck, 1992; Schinke and Matthäus, 1998; Schmale et al., 2016; Liblik et al., 2018). However, these improved oxygen conditions are short-lived because, in the long-term, the inflows enhance stratification and thereby reduce vertical oxygen transport (Conley et al., 2002).

In the shallower regions, where the halocline is absent, but a seasonal thermocline restricts vertical mixing, oxygen consumption could lead to temporal near-bottom hypoxia and sediment phosphorus release in late summer-autumn (Lukkari et al., 2009; Puttonen et al., 2014, 2016; Walve et al., 2018). For instance, such seasonal hypoxic events have occurred in the northern Baltic coastal areas and Åland archipelago, influenced by large-scale eutrophication driven by nutrients from agriculture and local fish farms (Bonsdorff et al., 1996). Sedimentation of organic matter, stimulated by nutrient inputs, can cause severe oxygen deficiency under specific meteorological/hydrographic conditions, as observed in the southern Baltic in 1994 and 2002 (e.g. Conley et al., 2007; Powilleit and Kube, 1999).

One of the shallow areas where seasonal hypoxia can occur is the Gulf of Riga (GoR) in the eastern part of the Baltic Sea (e.g., Berzinsh, 1995 and references therein; Aigars and Carman, 2001; Eglīte et al., 2014; Aigars et al., 2015). The Gulf of Riga is a semi-enclosed basin (Fig. 1) with a surface area of 16,330 km^2, a volume of 424 km^3, and a mean depth of 26 m (Ojaveer, 1995; HELCOM, 2002). Its deeper central area, situated east of the Ruhnu island, has depths of up to 56 m (Stiebrins and Väling, 1996). The water and salt budgets of the gulf are governed by river discharge, precipitation-evaporation balance, and water exchange with the Baltic Proper through the connecting straits. The long-term (1950–2015) mean river runoff is about 36 km^3 year^{-1} (Johansson, 2016), and the average freshwater flux due to the difference between the surface precipitation and evaporation rates is about 2.5 km^3 year^{-1} (Omstedt et al., 1997). Five larger rivers (Daugava, Lielupe, Gauja, Pärnu, and Salaca) enter the southern and eastern part of the gulf, with the Daugava river contributing about 70% of the total riverine input (Yurkovskis et al., 1993). AssumingConsidering the gulf's water volume and salt content annual balance, Lilover et al. (1998) estimated that its water renewal period would be about three years.

GoR water exchange with the Baltic Proper takes place via the Irbe Strait in the west (about 70-80% of water exchange) and the Suur Strait in the north (Astok et al., 1999; Petrov, 1979). The Irbe Strait has a sill depth of 25 m and a cross-section area of 0.4 km^2, while these hydrographical features are 5 m and 0.04 km^2, respectively, for the Suur Strait. Lips et al. (1995) suggested that

the gulf's deep ~~layer water~~waters could be renewed in summer by inflows of saltier water from the eastern Baltic Proper over the sill in the Irbe Strait – which is deeper and wider – while inflows through the shallow Suur Strait are arrested in the surface layer. The near-bottom inflows through the Irbe Strait are intensified by the northerly and north-easterly winds, which cause upwelling events along the eastern coast of the Baltic Proper. Model simulations by Raudsepp and Elken (1995) also showed that strong

5 northerly wind events could create substantial near-bottom inflows of saltier Baltic Proper waters. However, when downwelling occurs along the eastern coast of the Baltic Proper, the inflowing water is warmer than that of the near-bottom ~~layer water~~waters in the Gulf of Riga in summer, and can spread buoyantly at the intermediate depths (Liblik et al., 2017).

Because of the shallowness of the basin, the entire water column is well mixed in winter. In summer, stratification is mainly

10 maintained by the seasonal thermocline, which begins developing in April and is at its strongest in August, while the contribution of haline stratification is relatively moderate (Stipa et al., 1999; Liblik et al., 2017). Based on CTD profiles from 1993–2012, Skudra and Lips (2017) revealed that the strongest stratification occurred in the years with the highest summer surface temperature and spring river discharge. A high correlation between the deep layer salinity in the Irbe Strait and the gulf was found by Skudra and Lips (2017), in accordance with the suggestion that the majority of water exchange between the Baltic Proper and the gulf occurs

15 through the Irbe Strait.

Based on data from 1963 to 1990, a statistically significant decreasing trend of oxygen concentration in August was found for the entire 20–50 m layer in the gulf (Berzinsh, 1995). No trend was detected after that (HELCOM, 2009). The latest monitoring data are not analyzed for long-term trends and inter-annual variations in near-bottom oxygen concentrations; rather, model outcomes are

20 used to describe the oxygen conditions (e.g., Jansson et al., 2020). It is well documented, however, that the anoxic and hypoxic areas have been expanding in the entire Baltic Sea in recent decades, due to both eutrophication and changes in climatic conditions (Hansson and Viktorsson, 2020; the analysis also included data from the Gulf of Riga).

Total annual nitrogen and phosphorus loads to the Gulf of Riga estimated for 2017 at levels of 90 544 and 2 427 t year^{-1}, respectively,

25 and are still higher than the maximum allowable inputs, according to the Baltic Sea Action Plan ~~(HELCOM, 2019).~~(HELCOM, 2022). Based on monitoring data since 1974, the phosphorus pool in the Gulf of Riga constantly increased until the mid-1990s (Yurkovskis, 2004), and was followed by stagnation (HELCOM, 2018a). Since riverine phosphorus input is <15% compared to phosphorus pool in the water column (Yurkovskis, 2004), the changes in the latter are largely governed by internal processes. The phosphate flux from the sediments to the water column depends on the near-bottom oxygen conditions with maximum values at low

30 DO concentrations. For instance, phosphorus release in the order of 100 µmol PO_4^{3-} m^{-2} d^{-1} was simulated at oxygen concentrations 1-2 mg l^{-1} (Eglīte et al., 2014). Thus, the reoccurrence of low near-bottom oxygen conditions supports sediment phosphorus release which counteracts potential decreases in the external phosphorus load to the gulf.

Data from regular monitoring cruises and targeted surveys revealed extensive near-bottom hypoxia in the Gulf of Riga in summer-

35 autumn 2018. Additionally, the weather conditions were extreme in summer 2018, manifested by a new air temperature maxima in Europe for April-September (Hoy et al., 2020). We have formulated three main questions for this study: Was the observed near-bottom hypoxia in the GoR in 2018 an exceptional event? What were the reasons behind the observed hypoxia? Was it a feature that could occur in the GoR and similar basins regularly and/or even more often in the future? We hypothesize that the earlier onset, strength, and duration of stratification, together with the unusually high winter river runoff, were the main contributors to the

40 extensive near-bottom hypoxia in 2018. If this hypothesis holds, then one may ~~predict~~speculate that the future occurrences of such events will likely increase. To test our hypotheses, we analyzed oceanographic and meteorological conditions in 2018, and compared them with the preceding years (2012-2017) and long-term means and variability.

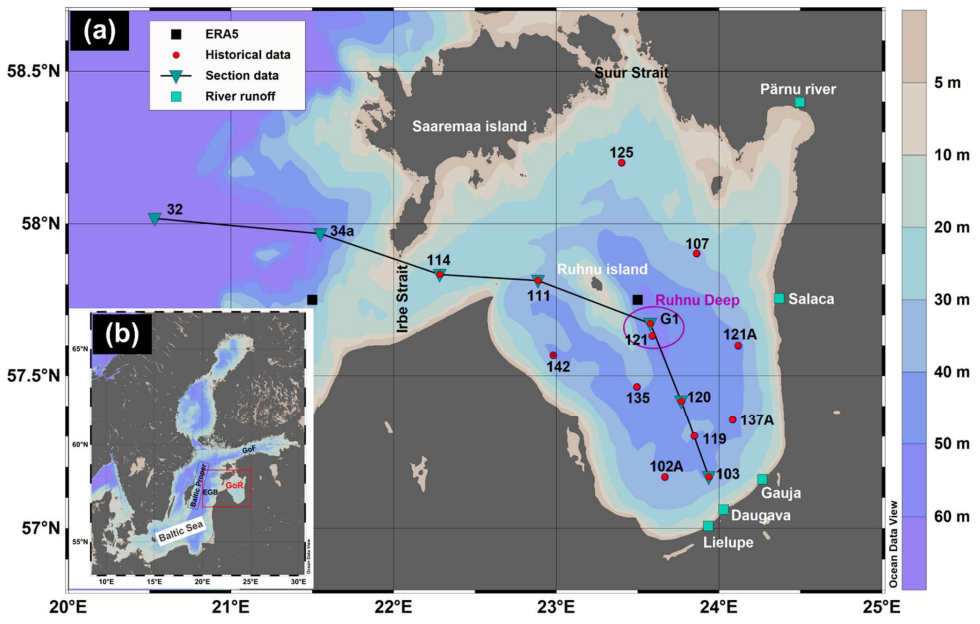
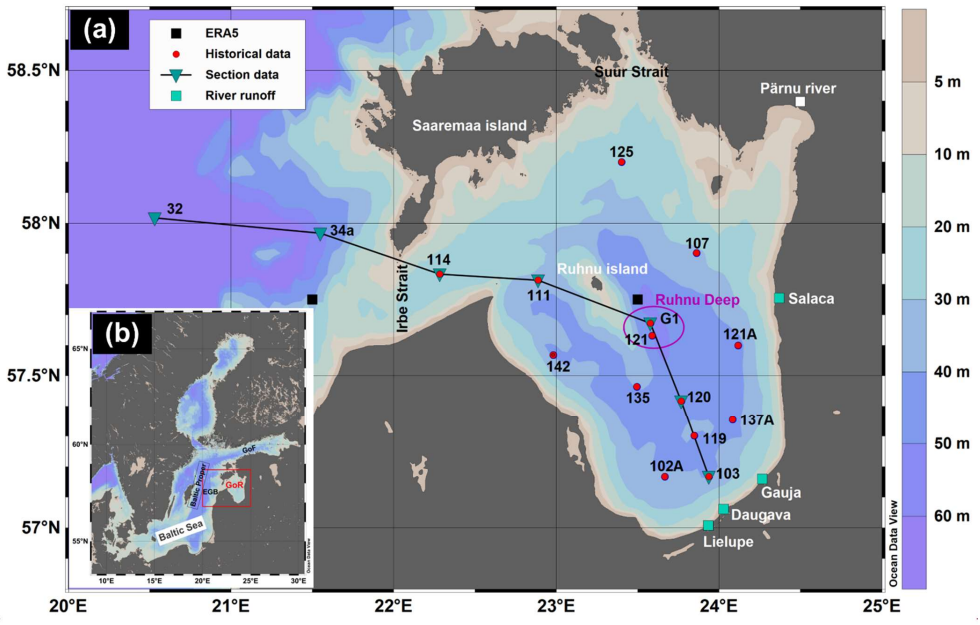
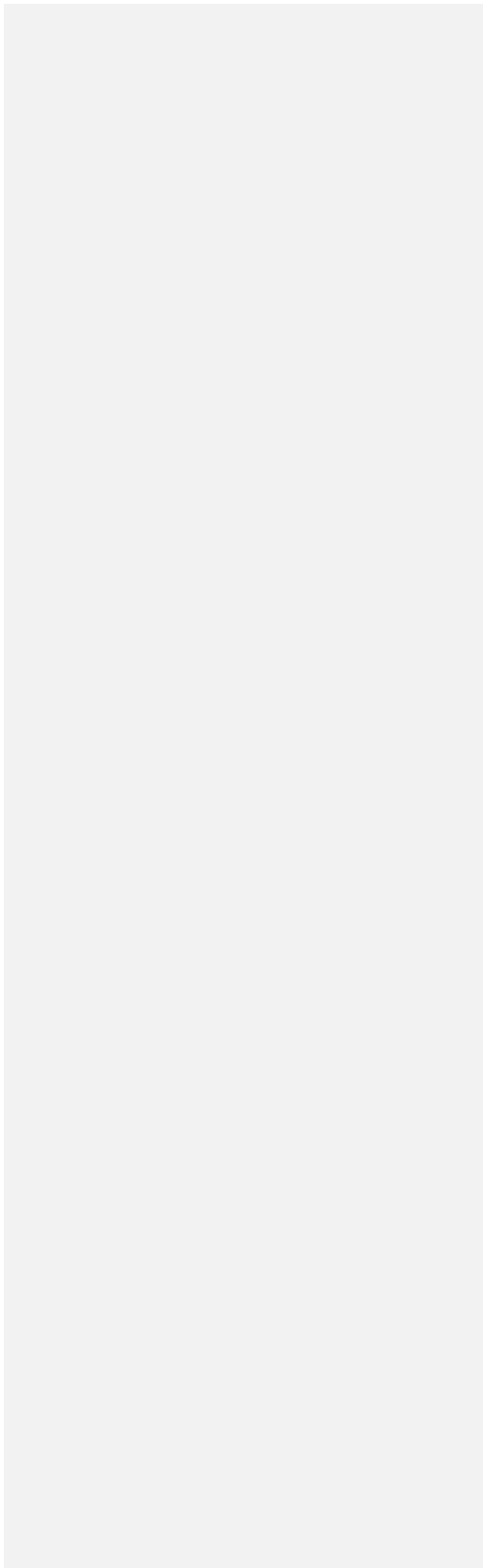



Figure 1. (a) - Map of the study area in the Gulf of Riga (GoR) with bottom topography. Red-filled circles represent the locations of monitoring stations. Inverted triangles represent the stations used for section figures. Black-filled squares represent the grid cell center points of ERA5 data (grid cell resolution 0.25º x 0.25º). Green-filled squares denote rivers from where runoff data was used.

EGB – Eastern Gotland Basin, and GoF – Gulf of Finland. (b) – Study area in the Baltic Sea. This map was generated using Ocean Data View 5.2.0 software (Schlitzer, 2019).

2. Material and methods

Historical data on the near-bottom temperature, salinity, dissolved oxygen, and nutrient concentrations were downloaded from the Estonian environmental monitoring information system (KESE), Latvian environmental monitoring databases, ICES/HELCOM database, and SeaDataNet Pan-European infrastructure for ocean and marine data management (http://www.seadatanet.org). More consistent near-bottom oxygen data were available from 2005; therefore, we limited the analysis to 2005–2018. HELCOM guidelines (HELCOM, 2017) were followed for the sampling and analytical detection of oxygen and nutrient concentrations in the monitoring laboratories.

Vertical profiles of temperature, salinity, and dissolved oxygen with temporal resolution of at least six times a year are available since 2012. The profiles were recorded using an Ocean Seven 320plus CTD probe (Idronaut s.r.l.) onboard r/v Salme during Estonian and Latvian monitoring cruises (stations are shown in Fig. 1). Salinity and density anomaly are shown in the present study as Absolute Salinity (g kg^{-1}) and Sigma-0 (kg m^{-3}), and were calculated using the TEOS-10 formula (IOC et al., 2010). The oxygen sensor (Idronaut s.r.l.) attached to the OS320plus probe was calibrated prior to each cruise. Oxygen profiles used for the analysis were quality-checked against the laboratory analysis of water samples using an OX 400 l DO (WWR International, LCC) analyzer. The accuracy of the Idronaut oxygen sensor is 0.1 mg l^{-1}, while the accuracy of the laboratory dissolved oxygen analyzer is 0.5 % of the measured value. The primary data set used to characterize the water column structure and dissolved oxygen and phosphates concentrations in 2018 was collected on 9-10 January, 17-18 April, 30 May, 11 July, 25 August, and 26-27 October.

The depth of the upper mixed layer (UML) was defined according to Liblik and Lips (2012) as the minimum depth, where $\rho_z - \rho_3 > 0.25$ kg m^{-3}, where ρ_z is the density anomaly at depth z and ρ_3 at depth 3 meters. The depth of the near-bottom mixed layer (NBL) was found similarly to UML, as the maximum depth, where $|\rho_z - \rho_{last}| > 0.1$ kg m^{-3}, where ρ_{last} is the density anomaly at the maximum depth of a profile. Oxygen concentration ≤ 2.9 mg l^{-1} (2 ml l^{-1}) was used as the threshold concentration for defining hypoxia, and the upper boundary of the hypoxic layer was found as the minimum depth at which oxygen concentration was below the threshold. The estimated depth of the upper boundary of the hypoxic layer at station G1 and the gridded topography (EMODnet Bathymetry Consortium, 2020) were used to find the lateral extent of the hypoxic area, assuming ~~that~~an even horizontal depth distribution for the ~~border~~occurrence of hypoxia ~~was spatially horizontal~~. The sea depth at station G1 is 54 m (Fig. 1). The profiles covered – in most cases – the depth range from 2 to 52 m. The water column structure was characterized by temperature, salinity, and density in the UML and NBL and potential energy anomaly (PEA; Simpson et al., 1990) calculated as

$$PEA = \frac{1}{h}\int_{-h}^{0}(\bar{\rho} - \rho)gz\,dz, \quad \text{where} \quad \bar{\rho} = \frac{1}{h}\int_{-h}^{0}\rho\,dz, \tag{1}$$

where h is the water column depth (50 m), ρ is water density, z is depth (vertical coordinate), and $g = 9.81\ m\ s^{-2}$.

Meteorological data for 1979-2018 were extracted from the ERA5 dataset (Hersbach et al., 2018) via Copernicus Services for characterizing local conditions in the gulf and upwelling-favorable conditions along the eastern coast of the Baltic Proper. Based on hourly data from a grid cell in the central gulf (see Fig.1), the monthly mean net solar radiation, air temperature (2 m above surface) and wind speed (at the 10 m height) in 2018 were calculated and compared with monthly mean values and variability in 1979–2018. ~~River runoff data~~Runoff data of rivers Salaca, Gauja, Lielupe, and Daugava (Fig. 1) from 1993 to 2018 were received from the Latvian Environment, Geology and Meteorology Center ~~and contained~~as the estimated monthly runoff (m^3 s^{-1} ~~) of rivers Salaca, Gauja, Lielupe, and Daugava (Fig. 1) in 1993 2018)~~. River Pärnu runoff data were obtained from the Estonian Weather Service.

For a more detailed analysis of the impact of meteorological and hydrological conditions on the development of stratification, changes in potential energy anomaly due to surface heating-cooling (S_b), wind mixing (S_m), and freshwater discharge from rivers (S_r) were estimated for the years 2012-2018

$$\frac{dPEA}{dt} = S_b + S_m + S_r. \tag{2}$$

The two former parameters were calculated as suggested by ~~(Simpson et al., 1990)~~Simpson et al. (1990)

$$S_b = \frac{\alpha_v g Q_{TOT}}{2c_p} \text{ and } S_m = -\delta C_D \rho_a \frac{W^3}{h}, \tag{3}$$

where Q_{TOT} is the surface heat flux and W is the wind speed. Q_{TOT} is the sum of the shortwave radiative heat flux, longwave
5 radiative heat flux, sensible heat flux, and latent heat flux estimated using ERA5 data and surface salinity obtained from CTD casts interpolated between the measurements. Thermal expansion coefficient α_v was calculated using the TEOS-10 formula (IOC et al., 2010) and specific heat of seawater $c_p = 4000\,J\,(kg\,K)^{-1}$ was applied. In the formula for the shortwave radiative heat flux, an average albedo of 0.055 was used (Groeskamp and Iudicone, 2018; Séférian et al., 2017). Otherwise, we used the same methods of calculating surface heat flux components as Liblik and Lips (2012). For estimating S_m, constant values of efficiency of mixing $\delta =$
10 10^{-3} and air density $\rho_a = 1.25\,kg\,m^{-3}$ were applied and effective drag coefficient C_D was calculated according to (Wu, 1982). The changes in stratification due to river discharge were estimated using monthly runoff from the previous month. The flow in m^3 s^{-1} was multiplied by a constant, which was found assuming that the average yearly change in PEA in 2012-2018 was equal to the change caused by the average runoff of 36 km year^{-3} evenly distributed over the entire surface area of the gulf.

15 Wind data from a grid cell outside the gulf, but close to the Irbe Strait (see Fig. 1), were extracted from ERA5 data to calculate the north-northeast (NNE) component of wind stress as $\tau_{NNE} = C_D \rho_a |W| W_{NNE}$, where W_{NNE} is the wind speed component directed towards NNE (south-southwest wind component). It is used to find the periods with upwelling-favorable conditions along the eastern coast of the Baltic Proper and for a more detailed analysis of inflows-outflows through the Irbe Strait in 2012-2018. Cumulative wind stress is calculated by summing up the hourly NNE components of wind stress multiplied by the time step of 1 hour starting
20 from 1 January each year.

We introduce a ~~rough~~coarse method estimating oxygen consumption rates in the gulf NBL. The considered physical processes contributing to the measured changes in salinity and oxygen concentration in the NBL were: 1) vertical diffusion and 2) lateral advection and mixing. Diffusive flux of salt and oxygen through the border between the NBL and the water column above was
25 estimated using a similar approach as Stoicescu et al. (2019)

$$DIFF_S = -k * \frac{\partial S}{\partial z} \text{ and } DIFF_{O_2} = -k * \frac{\partial O_2}{\partial z}, \tag{4}$$

where the vertical diffusivity coefficient is calculated as $k = \frac{\alpha}{N}$, α is the empirical intensity factor of turbulence (we applied a constant value $\alpha = 1.5 * 10^{-7}$ m^2 s^{-2}), and N is the Brunt-Väisälä frequency defined by the vertical density gradient. The changes in salinity and oxygen concentration in the NBL can be found by multiplying the value of diffusive fluxes with the time between two
30 measurements ($t2$-$t1$) and dividing it with the thickness of the NBL (h_{NBL}) as

$$\Delta S^{DIFF} = DIFF_S * \frac{t2-t1}{h_{NBL}} \text{ and } \Delta O_2^{DIFF} = DIFF_{O_2} * \frac{t2-t1}{h_{NBL}}. \tag{5}$$

Knowing salinities of inflowing waters and gulf NBL waters at time steps $t1$ and $t2$ and the changes due to vertical diffusion, we can estimate the proportion of inflowing waters in the near-bottom water mass at time step $t2$. Using this proportion, we can also
35 estimate the expected changes in the NBL oxygen concentration due to lateral transport and mixing as

$$\Delta O_2^{ADV} = \left(O_2^{t1}(114) - O_2^{t1}(G1)\right) * \left[\frac{Sal^{t2}(G1) - Sal^{t1}(G1)}{Sal^{t1}(114) - Sal^{t1}(G1)}\right], \tag{6}$$

where $Sal^{t1}(G1)$ and $O_2^{t1}(G1)$ are salinity and oxygen concentration in the NBL at station G1 and $Sal^{t1}(114)$ and $O_2^{t1}(114)$ at station 114 in the Irbe Strait (see Fig. 1) at an initial time step $t1$. $Sal^{t2}(G1)$ is measured salinity in the NBL at station G1 at time step $t2$ corrected by the estimated salinity change due to vertical diffusion.

40

Due to oxygen consumption, measured oxygen concentration in the NBL at station G1 at time step $t2$ ($O_2^{t2m}(G1)$) should be lower than that found when considering only changes due to physical processes since no production is expected in the near-bottom layer that is well below the euphotic depth. Oxygen depletion due to consumption can be found as the sum of the measured oxygen depletion and changes in concentration due to diffusion and lateral advection and mixing

$$\Delta O_2^{CONS}(G1) = -(O_2^{t2m}(G1) - O_2^{t1}(G1)) + \Delta O_2^{DIFF} + \Delta O_2^{ADV}. \tag{7}$$

Oxygen consumption rate per unit bottom area is calculated as

$$O_2^{CONS\,rate} = \frac{\Delta O_2^{CONS}}{t_2 - t_1} * h_{NBL}. \tag{8}$$

We have chosen the time step of one month or longer to estimate oxygen consumption rates based on the distance between the Irbe Strait and the Ruhnu Deep (120 km, measured along the deeper area of the gulf) and average (monthly) flow rates in the gulf of 5 cm s^{-1} (e.g., Soosaar et al., 2014; Lips et al., 2016). ~~The applicability of the introduced consumption rate estimates is more thoroughly analyzed in the Discussion (Sect. 4).~~

The same methods were used to estimate phosphate fluxes due to physical processes and phosphorus release from the sediments. The measured concentrations in the near-bottom layer at station G1 were assigned to the gulf's water and at station 114 to the inflowing water. In Eqs. (4) – (8), oxygen concentration was replaced by phosphate concentration and the difference in measured and expected phosphate concentrations in the gulf near-bottom layer was associated with the phosphorus release from the sediments. Since the vertical resolution of nutrient sampling was scarce (step was 10 m), we used only the deepest measured phosphate concentration as the value characterizing the entire NBL, and the vertical gradient was estimated between the phosphate concentrations at the deepest sampling point and 10-12 m above it.

3. Results

3.1. Inter-annual variability of dissolved oxygen in the near-bottom layer

We characterized the long-term development of oxygen conditions in the Gulf of Riga using near-bottom oxygen measurements at the deepest stations G1 and 121 (bottom depth 54 m) and yearly average late summer (August) and autumn (October-November)
5   near-bottom oxygen concentrations at all stations with depth >= 40 m (see station locations in Fig. 1). Based on the data obtained from the deepest stations, late summer-autumn hypoxia occurred in about 50% of years in 2005–2018 (Fig. 2). No hypoxia was observed in 2006–2011, except for one value close to 2.9 mg l^{-1} in 2009, but note ~~low~~the lower sampling frequency. Hypoxic conditions have been recorded every year since 2012, ~~with the exception of in~~except for 2016 and 2017. Based on the data from all monitoring stations from 2005-2018, no trend in the deep layer oxygen concentrations was detected in summer, but a statistically
10   significant (p < 0.05) trend at a rate of 0.45 mg l^{-1} year^{-1} was found in autumn ($R^2 = 0.50$, n = 13). Thus, the monitoring data suggest that the hypoxic conditions observed in 2018 are – in general – in line with the long-term trend.

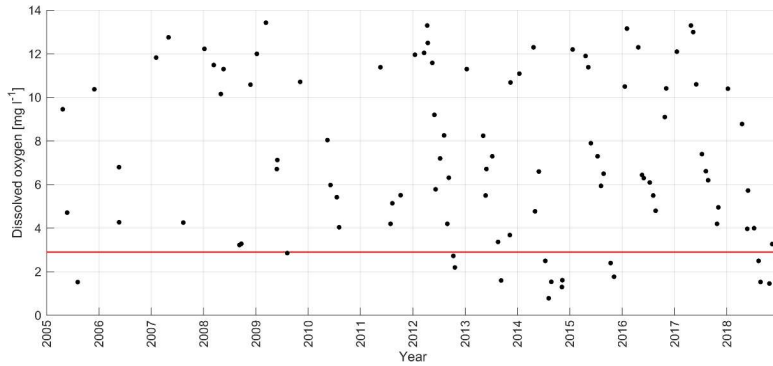



Figure 2. Inter-annual variability of near-bottom dissolved oxygen concentration at monitoring stations G1 and 121 in 2005–2018.
15   The red line denotes the oxygen concentration 2.9 mg l^{-1} (threshold concentration for hypoxia).

We studied the links between the long-term trend and variability of near-bottom oxygen and other environmental parameters, such as salinity and nutrient concentrations. No significant trend in near-bottom salinity was revealed in 2005-2018. Using simultaneously
20   measured near-bottom salinity and oxygen values at station G1 from August to November in 2005-2018, we found a statistically significant ($R^2 = 0.24$, n = 36, p < 0.05) negative relationship – low oxygen concentrations corresponded to high salinity values. However, there are examples where hypoxia occurred at salinities 5.8 g kg^{-1} (in 2012 and 2015) and did not ~~exist~~ at 6.5 g kg^{-1} (in 2010).

25   The analysis of near-bottom phosphate concentrations at stations with depth >= 40 m revealed a statistically significant increase in concentrations in late summer (0.08 μM year^{-1}, $R^2 = 0.47$, n = 14) and autumn (0.12 μM year^{-1}, $R^2 = 0.34$, n = 13). A statistically significant negative correlation was obtained between the deep layer oxygen and phosphate concentrations in autumn ($R^2 = 0.79$, n = 13, p<0.05). The near-bottom layer oxygen in autumn also significantly correlated with the next year winter (January) phosphate concentration in the entire water column ($R^2 = 0.45$, n = 9, p<0.05). Thus, the impact of the hypoxia deepening is also seen in the
30   trends of phosphate concentrations.

3.2. Seasonal and inter-annual variability in the vertical distribution

Based on the vertical profiles of dissolved oxygen collected on an at least bi-monthly basis in 2012-2018, a clear seasonal pattern ~~is~~was apparent at all depths, with the largest amplitude occurring in the near-bottom layer (Fig. 3a). The lowest oxygen concentrations were measured in late summer/autumn, but the oxygen levels did not always drop below the hypoxia threshold (as in 2016 and 2017). The ~~deepest minimal~~lowest oxygen concentrations were observed in 2014 (0.8 mg l^{-1}) and 2018 (1.5 mg l^{-1}). As pointed out above, hypoxia was observed in 2012-2015 and 2018, but the duration and vertical extent of hypoxia differed between the years (Fig. 3a, Table 1). The first occurrence of the seasonal hypoxia was ~~first detected~~observed in July in ~~the year~~ 2014, August in 2018, September in 2013, and October in 2012 and 2015. The upper ~~border~~boundary of the hypoxic layer was at its shallowest depth in 2018 (45.0 m). Accordingly, the estimated spatial extent of hypoxia was the largest in 2018, when the hypoxic waters covered 5.2% (830 km^2) of the gulf's bottom area. In the other years with hypoxia (2012-2015), the estimates of the bottom area covered by hypoxic waters did not differ greatly, varying between 2.1% and 2.7% (340-430 km^2).

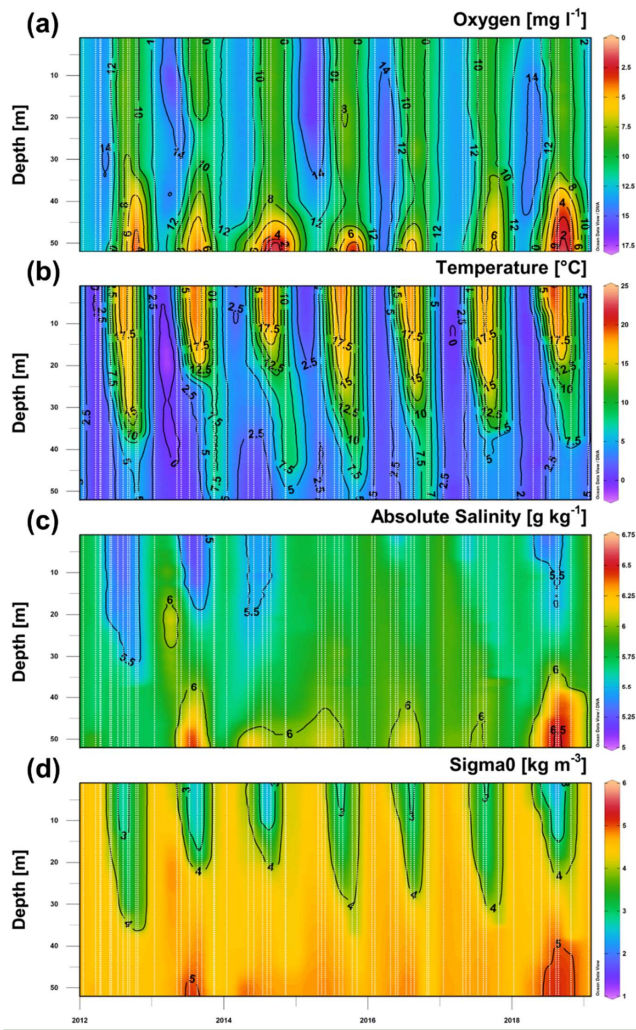



Figure 3. Time series of the vertical distribution of oxygen concentration (a), temperature (b), salinity (c), and density anomaly (d) at stations G1 and 121 in 2012-2018 (including January 2019). Vertical white dashed lines mark the time of measured profiles.

Seasonal patterns also ~~dominate~~dominated the variability of vertical distributions of temperature, salinity and density anomaly (Fig. 3b-d), but certain inter-annual differences in water column parameters can be noticed (Table 1). The observed UML temperature maxima were higher in the summers of 2014 and 2018. Lower summer UML salinities ($\leq$5.2 g kg^{-1}) were observed in 2012, 2013, and 2018, and increased NBL salinity values ($\geq$ 6.5 g kg^{-1}) were registered in the summers of 2013 and 2018. The largest density

10   differences between the bottom and surface layer, 3.4 kg m^{-3} and 3.5 kg m^{-3} – which ~~are~~were mostly associated with high UML temperatures – were found in 2014 and 2018. High NBL salinity and low UML salinity contributed to the observed relatively strong water column stratification in 2013 (the third-strongest stratification in 2012-2018), although the summer UML temperature

remained low in 2013 (Table 1). The weakest vertical stratification was observed in 2017, when the density difference between the NBL and UML was close to 2.0 kg m^{-3}.

Thus, the years with strong stratification (2013, 2014 and 2018; Table 1) ~~related to~~were associated with high UML temperature, low UML salinity, and high NBL salinity were among those with near-bottom hypoxia. In 2017, the stratification was the weakest, and hypoxia did not develop. Still, the density difference between the NBL and UML was weaker in 2012 and 2015 than in 2016 – but in 2012 and 2015, hypoxia was observed, whereas in 2016, it was not. ~~We suggest that vertical stratification is the key factor that~~

~~influences the development of hypoxia, but the overall stratification of the water column alone does not explain the occurrence, duration, and spatial extent of hypoxia.~~ A further, more detailed analysis of water column stratification is presented in Sect. 3.4 together with the description of meteorological and hydrological forcing data.

5 Table 1. Characteristics of seasonal hypoxia and stratification parameters in the Gulf of Riga in 2012-2018, based on CTD profiles from May to November at stations G1 and 121. Observed maxima of UML temperature, NBL salinity, and density difference between NBL and UML and minima of UML salinity are given.

Year	Earliest hypoxia detection	Min. depth of hypoxia	Max. hypoxic area	UML max temperature	UML min salinity	NBL max salinity	NBL-UML density
	month	m	% (km^2)	°C	g kg^{-1}	g kg^{-1}	kg m^{-3}
2012	October	48.5	2.7 (430)	18.97	5.16	5.77	2.20
2013	September	49.0	2.4 (380)	18.59	5.21	6.51	2.72
2014	July	49.0	2.4 (380)	23.46	5.28	6.08	3.38
2015	October	49.5	2.1 (340)	19.41	5.65	5.82	2.22
2016	-	-	-	19.37	5.38	6.21	2.35
2017	-	-	-	18.50	5.26	6.01	2.05
2018	August	45.0	5.2 (830)	22.36	5.17	6.51	3.46

3.3. Temporal development of hypoxia in 2018

To demonstrate the development of hypoxia and vertical stratification in 2018 in more detail and to compare it with that of the previous year without hypoxia, we present vertical profiles of temperature, salinity, density, and dissolved oxygen concentration in the Ruhnu Deep in 2017 and 2018 (Fig. 4). A major difference between the years is evident in a much faster decrease of near-bottom 15 oxygen concentrations in spring 2018 than in 2017. ~~This could be related to~~ Also, the ~~differences in~~ development of vertical stratification in ~~the springs of~~ spring-early summer differed between these two years. ~~Salinity~~In 2018, salinity stratification in the deep layer was ~~already~~ established in the middle of April ~~2018~~, and ~~two pycnoclines were~~ a very strong seasonal thermocline was formed by the end of May ~~2018. The water column was well mixed at the end of April~~. In 2017, the seasonal thermocline was remarkably weaker in the beginning of June, compared to late May of 2018, and ~~although the seasonal thermocline developed by~~ 20 ~~the end of May, neither the saltier near-bottom waters nor the deep~~no secondary pycnocline ~~was observed~~developed in ~~summer 2017. We suggest that~~ the deep layer ~~stratification influenced the near-bottom oxygen depletion in the gulf~~ in spring-summer ~~2018 by restricting mixing between the near-bottom layer and the water column above.~~.

~~The formation of the saltier near-bottom layer and the deep stratification in a sea basin separated from the open sea by a sill must~~ 25 ~~be related to the inflow of saltier and denser waters from the open sea. The~~The vertical sections of oxygen, salinity, and temperature (Fig. 5) demonstrate the spreading of waters from the eastern Baltic Proper to the Gulf of Riga over the Irbe Strait sill ~~can be demonstrated by the vertical sections of oxygen, salinity, and temperature (Fig. 5). Based on the measurements~~in late May and July 2018. However, at the end of ~~May, the intrusion of saltier waters over the sill is evident up to station 111. Higher temperatures associated with the saltier water in the near-bottom layer at station 111 could~~August, the distribution patterns indicate that outflow 30 from the ~~mixing of~~ gulf likely prevailed below the seasonal thermocline through the Irbe Strait (Fig. 5 lower panel).~~waters with the warmer waters from the Baltic Proper.~~ Oxygen concentrations in the near-bottom layer in the central gulf ~~and towards the Daugava river mouth in the southern gulf~~ were at a level of 60% saturation. ~~Low temperatures of this near-bottom water mass suggest that it had been formed in winter or early spring as a mixture of local Gulf of Riga winter waters and saltier waters originating from the Baltic Proper.~~

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~~In July, the deep area around monitoring station G1 was filled with saltier waters, and oxygen concentrations had~~ in late May, decreased further ~~to 40% of saturation (< 5 mg l⁻¹). The measurements in late August suggest that the further filling of deeper areas with saline water continued between the surveys – salinity increased at all deeper monitoring stations)~~ by mid-July and hypoxic conditions with oxygen saturation below 20% were established by the late August. We also point to an increase of salinity in the water layer of 35-45 m, which is well seen on the consecutive profiles measured in July and August at station G1 (Fig. 4). ~~This could be related to the inflow of denser waters in July-August that moved the "old" near-bottom waters upwards. Hypoxic conditions with oxygen saturation below 20% were observed in the near-bottom layer of the central gulf. However, the salinity, temperature, and oxygen distributions in the deep layers near the Irbe Strait indicate that outflow from the gulf likely prevailed below the seasonal thermocline at the end of August 2018 (Fig. 5 lower panel).~~

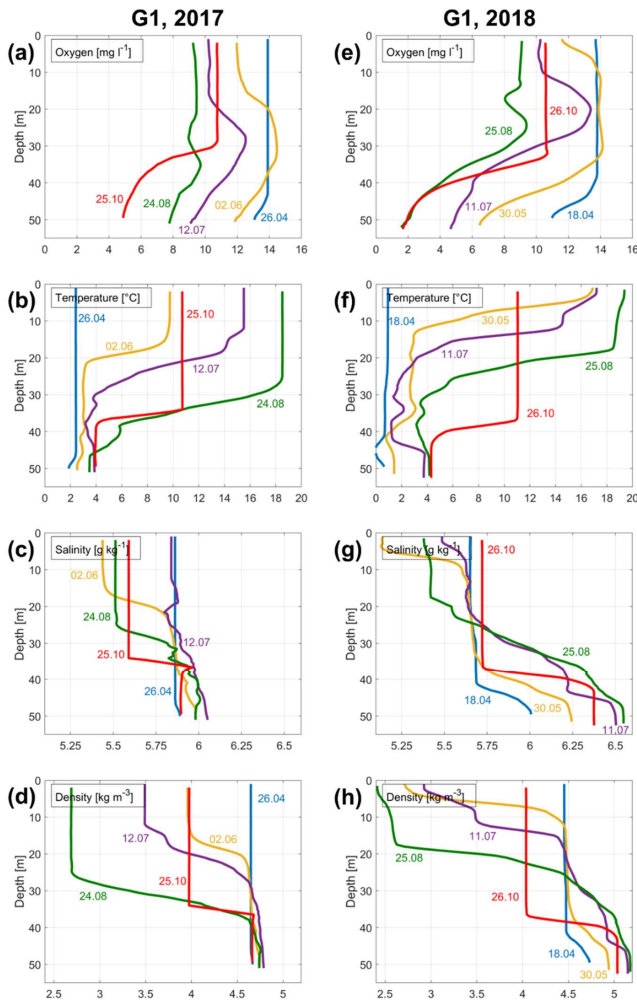



Figure 4. Vertical profiles of dissolved oxygen concentration (a, e), temperature (b, f), salinity (c, g), and density anomaly (d, h) measured in the Ruhnu Deep (station G1, see location in Fig. 1) in 2017 (left panels) and 2018 (right panels).

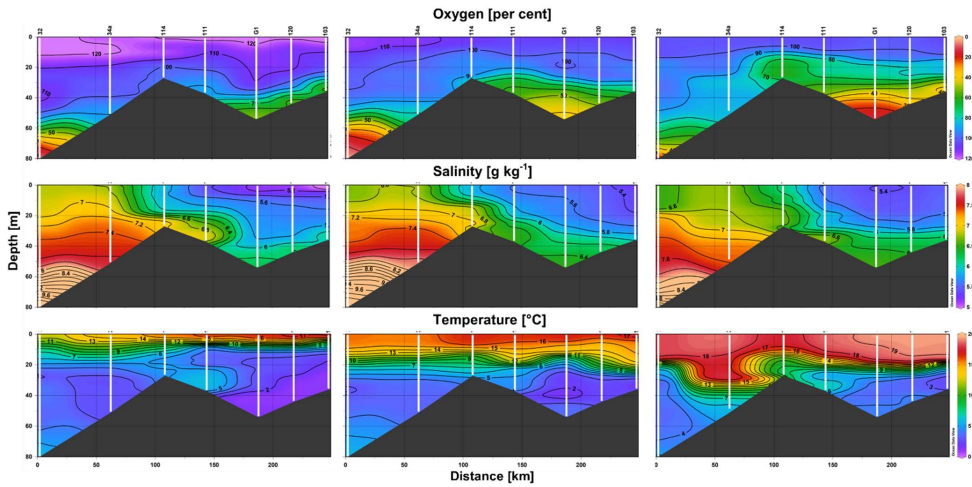
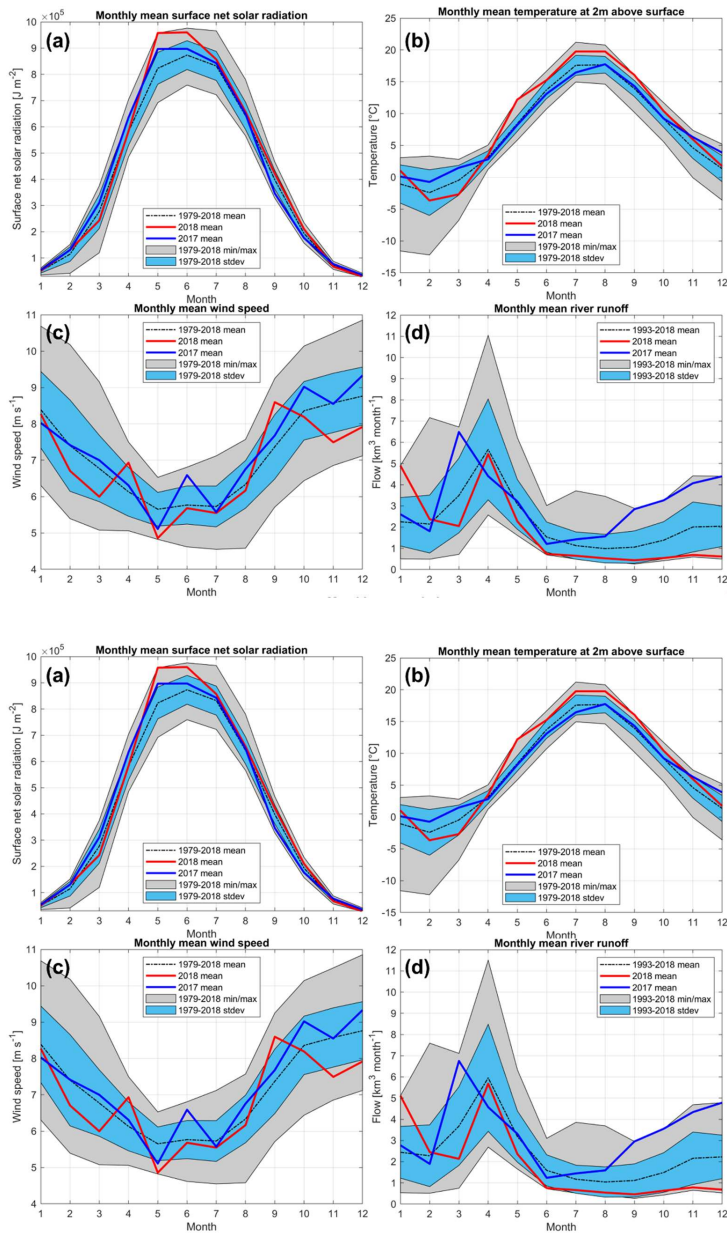



Figure 5. Vertical sections of oxygen saturation (upper panels), salinity (center panels), and temperature (lower panels) on 30 May (left panels), 11 July (center panels), and 25-26 August (right panels) 2018 along the route from station 32 in the Baltic Proper through the Irbe Strait to station 103 near Daugava river mouth in the Gulf of Riga (see the locations in Fig. 1).

3.4. Analysis of meteorological and hydrological conditions

~~The above analysis showed that vertical stratification is a major factor influencing the development of near-bottom hypoxia in the Gulf of Riga. Strong stratification could be related to high surface radiation and weak winds, as well as large river runoff and the inflow of saltier waters into the near-bottom layer.~~ Solar radiation in 2018 was higher than that of the long-term average for all months from spring to autumn~~, with the highest monthly mean value during the observation period being in 2018 in May (Fig.~~ (Fig. 6a). Seasonal variation of air temperature in 2018 differed from the average, as well, with a rapid increase in April-May and higher monthly mean values than the long-term averages until October (Fig. 6b). ~~Monthly mean air temperatures in July-September 2018 were in the top of 5 warmest years in 1979-2018.~~ The monthly average wind speed from February to August was lower in 2018 than the long-term mean for the respective month, except in April (Fig. 6c). The lowest wind speed for May in 1979-2018 was found in 2018~~, suggesting that the wind-induced mixing of the water column~~. All these anomalies in ~~May was the weakest in 2018, if compared with that of the other years. Thus, both the high heat flux and low mixing intensity~~meteorological conditions supported the observed fast development and strength of ~~a strong~~seasonal stratification in the GoR. As opposed to 2018~~. At,~~ the ~~same time,~~ solar radiation, air temperature, and wind speed in 2017 were mostly close to the long-term averages ~~—except the low wind speed in May and the high wind speed in June 2017 (Figs.~~(Figs. 6a-c).

5   Figure 6. Courses of monthly mean, minimum/maximum and standard deviation of (a) surface radiation, (b) air temperature, and
     (c) wind speed for the period of 1979–2018, and (d) river runoff for the period of 1993–2018. The monthly mean values of listed
     parameters for 2017 and 2018 are shown as blue and red lines, respectively. For meteorological parameters, ERA5 data are used
     from the central Gulf of Riga (see the location of the grid cell in Fig. 1).

A comparison of monthly river runoff values from 2018 with the long-term mean values (1993–2018) shows that the 2018 runoff was mostly lower than the long-term mean – although within standard deviation limits (Fig. 6d). An exception was found in January 2018, when runoff was the largest on the record, being more than twice as large (4.905.11 km^3 month^{-1}) as the long-term mean (2.2544 km^3 month^{-1}). The maximum or close to the maximum value of monthly river runoff was also observed in September-December 2017. A larger than average river runoff in autumn-early winter 2017-2018 could result in fresher surface waters, stronger vertical stratification, and larger nutrient and organic matter load to the Gulf of Riga.

The development of vertical stratification characterized by potential energy anomaly estimated using meteorological and river runoff data (Fig. 7) in general reflects the same differences between the years as the simple comparison of temperature, salinity and density in the UML and NBL (Table 1). The fastest development of stratification and the strongest stratification isat its peak were predicted for the summers of 2013 and 2018, and strong stratification was also characteristic for summer the summers of 2014, based on both the estimates using meteorological and runoff data and CTD profiles2016. The years 2012, 2015 and 2017 arewere among the years with the weakest stratification. However, very strong stratification is also predicted for 2016, which was not captured by the CTD measurements (note the high variability and the measurement step of about 1-2 months). Another relatively large discrepancyA critical difference between the prediction and CTD based estimates of PEA is seen for autumn 2013 – the prediction based on meteorological and hydrological data revealed a much longeryears can also be noticed during destratification in autumn. The longest stratified period than the measurements. This year was was found for 2013, which was a remarkable, year with the largest river runoff in spring (considering the period 2012-2018) and relatively high air temperatures in autumn. When analyzing the contribution of the three components in Eq. 1, the biggest influence comes from the warming and development of seasonal thermocline in spring and wind-induced mixing together with negative heat flux in autumn. River runoff had, in general, lower contribution to the development of stratification, although it is visible in early spring 2013 (Fig. 7). summer and autumn. The earliest decay of vertical stratification is predicted for 2016 and 2017 – the water column was fully mixed by the end of October in both years. In comparison, the water column was fully mixed remarkably later in 2015 – in the second half of November.

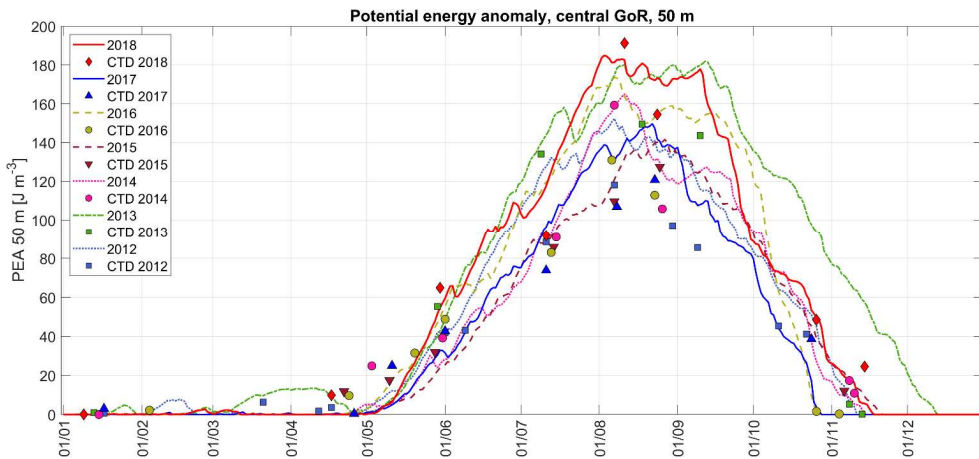



Figure 7. Changes in vertical stratification (potential energy anomaly, PEA, characterizing energy needed to mix the water column fully) in the central Gulf of Riga in ~~2001~~2012-2018 based on CTD profiles (markers) and estimated using meteorological (ERA5 data are from the central Gulf of Riga) and river runoff data (curves; the methods are presented in Sect. 2).

~~The fastest development of stratification in 2013 and 2018 is well seen in both the prediction and CTD measurements. The other years with stronger stratification in early summer were 2012 and 2016. A critical difference between the years can also be noticed in the stratification decay in autumn. The earliest disappearance of vertical stratification is predicted for 2016 and 2017 – the water column was fully mixed by the end of October. In comparison, the water column was fully mixed remarkably later in 2015 – in the second half of November. It could be why hypoxia was detected in late October and early November 2015 but was not observed in late October 2016 and 2017. We cannot prove whether hypoxia occurred in 2016 and 2017 since no data were available from late August to late October. However, the prolonged existence of stratification in autumn is one of the factors increasing the probability of the appearance of near-bottom hypoxia.~~

The analysis of the time series of along-coast component (NNE–SSW) of wind stress supports the described inflow-outflow suggestions for 2018 (see Sect. 3.3). Upwelling-favorable winds with negative wind stress τ_{NNE} exceeding –0.2 N m^{-2} that could be related to the inflows of saltier waters into the Gulf of Riga were observed in February-March, May, early June and late June 2018 (Fig. 8a). A major deviation from the long-term pattern is also evident in cumulative wind stress in 2018 – wind forcing from February to the end of July supported the near-bottom inflows (seen as the decrease in the cumulative wind stress; Fig. 8a). ~~From the beginning of August, the~~The winds from the opposite direction ~~– which could cause downwelling along the eastern coast of the Baltic Proper –~~ prevailed from the beginning of August. Thus, the inflows of sub-thermocline waters into the Gulf of Riga could have been blocked in late summer 2018, as also seen in Fig. 5 demonstrating the outflow of gulf deep layer waters to the Irbe Strait at the end of August.

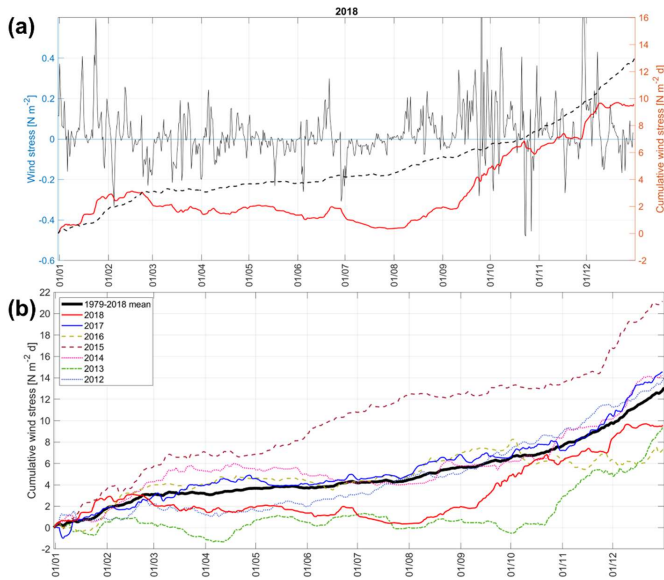



Figure 8. (a) Time series of along-coast (NNE–SSW) component of wind stress τ_{NNE} and cumulative wind stress in 2018 (6h moving average is shown). (b) Cumulative wind stress for each year in 2012-2018. Average cumulative wind stress curve for 1979-2018 is shown in both panels. Data were extracted from the ERA5 grid point outside the gulf (see location in Fig. 1).

Similar to 2018, the cumulative wind stress in 2013 largely deviated from the long-term mean (Fig. 8b). The inflow-favorable winds dominated in spring-summer, supporting the development of vertical stratification in the ~~gulf deep layer. Although these inflows potentially brought more oxygen to the NBL, hypoxia developed in late summer both years, probably due to high consumption of oxygen and enhanced stratification restricting vertical mixing.~~gulf's deep layer. A significant difference between these two years appeared in September – in 2013, the inflow-favorable winds persisted, while in 2018, the winds from opposite directions started to prevail. ~~This difference could be a reason for an earlier disappearance of hypoxia in 2013, since further inflows could bring enough oxygen to the NBL this year.~~ Inflow supporting wind conditions were also observed in late spring-summer 2014, forming a relatively thin NBL (with its boundary at 46 m), and hypoxia appeared already in July 2014. Almost no inflow supporting winds occurred in 2015~~, and probably no additional oxygen reached the gulf central area from the Irbe Strait.~~. Although stratification was not strong and the NBL salinity was low this year (see Table 1), hypoxia developed in 2015, but later – in late October ~~in 2015~~, while hypoxia in the other years was observed in July-September (Figs. 2 and 3). Cumulative wind stress graphs generally followed the long-term mean in 2016 and 2017 (Fig. 8b), and in these years, no hypoxia was observed. ~~We can conclude that in the case of meteorological conditions corresponding to the 1979-2018 average conditions, the probability of the development of near-bottom hypoxia is not high in the Gulf of Riga.~~

3.5. Estimates of oxygen consumption and sediment release of phosphates

We estimated fluxes of dissolved oxygen to the NBL at station G1 in summer 2018 due to vertical diffusion and lateral advection and mixing. Based on the gradient method (Eqs. 4-5), the estimated vertical diffusive flux varied between 0.26 and 0.43 mmol O_2 m^{-2} h^{-1}, corresponding to the changes in NBL oxygen concentration from 0.50 to 1.05 mg l^{-1} $month^{-1}$ (Table 2). ~~When converting the vertical fluxes per unit area into the changes in concentration, the average thickness of the NBL in the period under consideration was taken into account.~~ The estimated changes in oxygen concentration due to advection (Eq. 6) had comparable values, varying from 0.48 to 1.24 mg l^{-1} $month^{-1}$. According to the measurements, the NBL oxygen concentration continuously decreased in summer 2018, showing that oxygen consumption had to be large enough to exhaust oxygen brought by diffusion and advection~~,~~ and cause further oxygen depletion in the NBL. We found that ~~consumption~~respiration could cause oxygen depletion in the NBL by 2.94–4.24 mg l^{-1} $month^{-1}$ or, in total, by 16.2 mg l^{-1} from mid-April to late-August 2018 (Eq. 7). The ~~estimated~~corresponding consumption rate per unit bottom area (Eq. 8) varied from 1.53 to 1.75 mmol O_2 m^{-2} h^{-1} in 2018. ~~The relative variation of the latter was smaller than for depletion, since, assuming that consumption mainly takes place at the sediment surface, the same consumption rate leads to stronger depletion in the case of a thinner NBL.~~

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Table 2. Estimated changes in NBL salinity and oxygen concentration due to advection and diffusion (presented as the changes per month to ease the comparison between the periods) and estimated consumption rates from mid-April to late August 2018.

Period start (t1) and end (t2)		18.04-30.05	30.05-11.07	11.07-25.08
$O_2^{t1}(114)$	mg l^{-1}	13.42	12.46	11.08
$O_2^{t1}(G1)$	mg l^{-1}	12.01	8.27	5.16
$O_2^{t2m}(G1)$	mg l^{-1}	8.27	5.16	2.52

Measured O_2 depletion at G1	mg l^{-1} month^{-1}	2.67	2.22	1.76
$Sal^{t1}(114)$	g kg^{-1}	6.77	7.17	7.27
$Sal^{t1}(G1)$	g kg^{-1}	5.99	6.22	6.48
$Sal^{t2}(G1)$	g kg^{-1}	6.22	6.48	6.51
Average NBL thickness	m	9.5	9.5	12.0
Salinity change due to vertical diffusion	g kg^{-1} month^{-1}	-0.10	-0.09	-0.08
Vertical diffusion of O_2	mmol O$_2$ m^{-2} h^{-1}	0.43	0.32	0.26
O_2 change due to diffusion	mg l^{-1} month^{-1}	1.05	0.78	0.50
O_2 change due to advection	mg l^{-1} month^{-1}	0.48	1.24	0.68
O_2 change due to consumption	mg l^{-1} month^{-1}	4.20	4.24	2.94
O_2 consumption rate	**mmol O$_2$ m^{-2} h^{-1}**	**1.72**	**1.75**	**1.53**

For the periods when inflows through the Irbe Strait are absent, the only physical process contributing to the changes in oxygen concentration in the gulf NBL is vertical diffusion/mixing. We suggested that such conditions of no inflows occurred in summer 2015, based on prevailing winds (Fig. 8b) and observed low salinity in the NBL at station G1 (Table 1). The vertical diffusive flux of oxygen was estimated at 0.49 mmol m^{-2} h^{-1} ~~for~~in April-November 2015. If considering a similar oxygen consumption rate in 2015 as in 2018 (1.67 mmol O$_2$ m^{-2} h^{-1}), oxygen depletion in the NBL (with an average thickness of 16 m) could be 1.70 mg l^{-1} month^{-1}~~, taking into account the estimated average NBL thickness of 16 m in summer 2015~~. Thus, this rate is enough to cause hypoxia in the near-bottom layer of the central gulf in late October 2015, as it was observed (see Figs. 2 and 3), but not earlier.—

Simultaneously with the development of hypoxia, phosphate concentrations increased in the NBL at station G1 in summer 2018 (Fig. 9). The phosphate concentrations were already elevated in July when oxygen concentrations did not indicate hypoxic conditions at 2-3 m from the seabed. ~~However, hypoxia could occur at the sediment-water interface.~~ The estimated changes in phosphate concentrations due to ~~physical processes and the amount of phosphates released from the sediments were estimated using the same approach as was applied for estimating oxygen consumption (see Sect. 2). As seen in Table 3, the changes in phosphate concentrations due to~~ lateral advection and ~~lateral~~ mixing ~~were larger than due to~~ and vertical diffusion. ~~Considering both physical processes, the concentration estimates were lower than the measured values on the next monitoring campaign. This difference~~ varied between ~~the measured~~ 0.18 – -0.21 μM month^{-1} and ~~estimated concentrations was assigned to~~ -0.04 – -0.13 μM month^{-1}, respectively (Table 3). Since phosphate concentrations in the NBL continuously increased from spring to late summer (August), the sediment release of phosphates had to be large enough to compensate for the flux by physical processes and maintain the observed accumulation. The largest estimated phosphate flux from the sediments was 13.6 μmol m^{-2} h^{-1} for the period from the end of May to mid-July 2018. From late April to late May, the phosphate flux from the sediments was minimal, which might be explained by relatively high oxygen concentrations in the NBL. Although the oxygen concentrations decreased and fell below the hypoxia threshold from mid-July to late August, the estimated sediment release ~~was lower~~ for this period was lower (7.4 μmol m^{-2} h^{-1}) than from late May to mid-July.
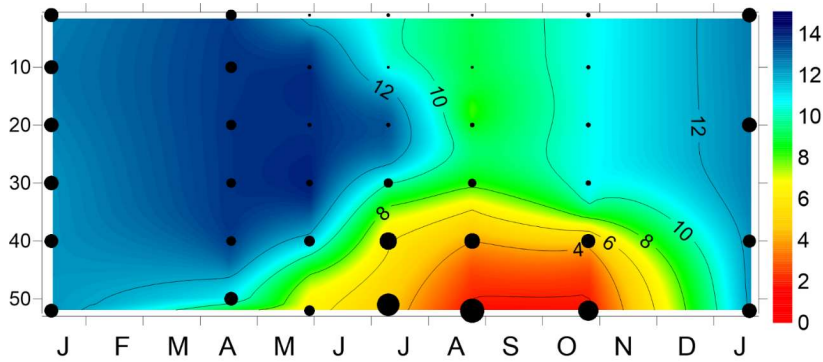
Figure 9. Time series of vertical distribution of oxygen and phosphate concentration at station G1 in the Gulf of Riga from January 2018 to January 2019. Phosphate concentrations are indicated as black dots. The size of the dots is proportional to the measured concentrations ranging from the lower detection range of 0.06 to 2.25 µM.

Table 3. Estimated changes in NBL phosphate concentration due to advection and diffusion and estimated sediment release of phosphates in the Gulf of Riga between the monitoring campaigns in 2018.

Period start (t1) and end (t2)		18.04-30.05	30.05-11.07	11.07-25.08
$PO_4^{t1}(114)$	µM	0.49	0.21	0.33
$PO_4^{t1}(G1)$	µM	1.12	0.82	1.95
$PO_4^{t2m}(G1)$ (measured)	µM	0.82	1.95	2.11
Average NBL thickness	m	9.5	9.5	12.0
PO_4 change due to diffusion	µM month^{-1}	-0.04	-0.05	-0.13
PO_4 change due to advection and lateral mixing	µM month^{-1}	-0.20	-0.18	-0.21
Estimated rate of the sediment PO₄ release	**(µM m^{-2} h^{-1})**	**0.4**	**13.6**	**7.4**

4. Discussion

Declining oxygen levels and more frequent hypoxia have been reported in many coastal environments, including the Baltic Sea (Caballero-Alfonso et al., 2015; Carstensen et al., 2014; Conley et al., 2009). ~~The present study concludes that the decreasing trend in oxygen concentrations in the Gulf of Riga near-bottom layer in summer–autumn stated earlier~~We found a similar tendency in the Gulf of Riga with more frequent hypoxia in recent years and a statistically significant decreasing trend of deep layer oxygen concentrations (based on data in autumn 2005–2018). Thus, in general, we can state that the observed extensive hypoxia in 2018 was in agreement with the long-term changes in the GoR oxygen dynamics (Berzinsh, 1995; HELCOM, 2009) ~~has continued since 2005. Near-bottom oxygen concentration fell below the hypoxia threshold in seven out of the analyzed 14 years (2005–2018), and the largest area of hypoxic bottoms was revealed in 2018. It is well known and~~. However, the reasons behind the largest extent of hypoxia, as observed in 2018, need further explanation.

It is well documented that the main causes of near-bottom hypoxia are elevated nutrient inputs, leading to high oxygen demand for organic matter decomposition, and topographic/hydrographic characteristics of coastal areas, restricting oxygen supply by physical processes (Carstensen et al., 2014; Virtanen et al., 2019). If oxygen consumption ~~rate~~ exceeds oxygen supply by vertical mixing and advection for a long enough period, hypoxia or even anoxia could occur (Fennel and Testa, 2019). Seasonal stratification is a major factor restricting oxygen supply to the near-bottom layer depending on its strength (Kralj et al., 2019) and the duration between its onset and decay (Fennel and Testa, 2019).

In 2018, fast warming of the surface layer and weak wind-induced mixing in spring resulted in strong vertical stratification. The peak of the spring bloom, which generates most of the sedimented organic material, is observed in the Gulf of Riga in April-May (Olli and Heiskanen, 1999; Purina et al., 2018). When the spring bloom material reaches the sediment surface, it triggers enhanced oxygen consumption, with the rate and delay depending on the bloom species composition, e.g., diatom-dinoflagellate ratio (Spilling et al., 2018). Aigars et al. (2015) found higher consumption rates in late spring-early summer than in late summer-autumn and related this result to the availability of degradable organic material, i.e., settling of spring bloom. Thus, the strength of stratification in spring-early summer is a crucial factor influencing the extent of seasonal hypoxia in the Gulf of Riga and similar coastal basins.

Since oxygen consumption at the sediment-water interface can have a large share in depth-integrated respiration (Boynton et al., 2018), separation of the near-bottom layer from the waters above may accelerate oxygen depletion in the NBL. For instance, Jokinen et al. (2018) suggested that a decrease of the water volume between the pycnocline and the seabed increased the probability of hypoxia occurrences in a shallow basin of the Archipelago Sea (Haverö). ~~We identified that near-bottom hypoxia in the central Gulf of Riga was often associated with higher NBL salinity that can be a result of inflows through the Irbe Strait (Lilover et al., 1998; Skudra and Lips, 2017). However, if originating from the near-surface layer, the inflows of saltier waters should feed the near-bottom layer of an enclosed basin with oxygen (e.g. Schmidt et al., 2021).~~We suggest that besides the strong seasonal stratification and reduced vertical mixing, the haline stratification in the deep layer that existed already in spring was a crucial precondition for hypoxia development in 2018. A similar thin near-bottom layer with higher salinity was observed in early summer 2014, and in both years, summer deoxygenation was higher compared to other years. The year 2018 was specific since additional inflows of saltier waters in summer caused an uplift of the almost oxygen depleted near-bottom waters. As a consequence, the boundary of hypoxic waters was at its shallowest depth, and the estimated extent of hypoxic bottoms was the largest in late summer-autumn 2018. Thus, although the development of hypoxia in 2018 was in accordance with the long-term trend, the co-occurrence of several factors made it an exceptional event.

Based on the introduced method, we estimated the oxygen consumption rate was estimated at 1.67 mmol O_2 m^{-2} h^{-1} for spring-summer 2018, comparable with the earlier measurements and calculations. Results from this study are. This result is higher than the estimates of consumption rates obtained for the Baltic Proper and the Gulf of Finland – 0.11-0.39 mmol O_2 m^{-2} h^{-1} (Koop et al., 1990) and 0.46-0.53 mmol O_2 m^{-2} h^{-1} (Conley et al., 1997), respectively, and closer to but slightly lower than the estimates based on the direct measurements in the Gulf of Riga by Aigars et al. (2015) – on average 2.3 mmol O_2 m^{-2} h^{-1}. One reason for the lower values obtained in our study might be related to the fact that the analysis by Aigars et al. (2015) was conducted using core samples collected at stations 119 and 120, which are situated in the southern Gulf of Riga, close to the main river mouths (see Fig. 1). On the other hand, our estimates are much higher than found for the deep areas of the Baltic Proper, although it is stated that the consumption rates there are recently acceleratedOn the other hand, our estimates are much higher than found for the deep areas of the Baltic Proper, although it is stated that the consumption rates there have accelerated recently (Meier et al., 2018). We used the estimated consumption rate to explain the occurrence of hypoxia in 2015 with relatively weak stratification and suggest that seasonal stratification lasted long enough to reach hypoxia levels in late October 2015. No hypoxia was observed in 2016, although seasonal stratification was strong at its peak, because the water column was fully mixed before the autumn monitoring cruise in late October. We suggest that a longer duration of the stratified season in recent years, as also revealed by other authors, e.g., Wasmund et al. (2019), has increased the probability of hypoxia occurrences in the near-bottom layer of seasonally stratified coastal basins in autumn.

Strong vertical stratification has been considered as a major factor restricting oxygen supply to the NBL due toWe analyzed the seasonal dynamics of vertical stratification depending on the local meteorological conditions to reveal the potential development of near-bottom oxygen conditions due to predicted climate changes. Stratification has strengthened in the Baltic Sea mostly due to increasedits strength (Kralj et al., 2019) and duration (Fennel and Testa, 2019). Stratification has strengthened in the Baltic Sea mostly due to the increase in surface layer temperature (Kniebusch et al., 2019; Liblik and Lips, 2019). In our assessment of the development of vertical stratification, according to Simpson et al. (1990), the surface heat flux and wind-induced mixing were the main contributors. River runoff had in general lower contribution to the development of stratification although haline stratification is often observed in Baltic Sea basins in winter-early spring (Liblik et al., 2020a; Stipa et al., 1999), as also revealed in the Gulf of Riga for the year with the highest river discharge – 2013. In addition, large river runoff could raise the nutrient and organic matter concentrations in the gulf (Yurkovskis, 2004) and, hence, contribute to the hypoxia development. to its changes. River runoff had, in general, a lower contribution, although its influence was seen, e.g., in early spring 2013, which was the year with the highest river discharge (considering the period 2012-2018).

In 2018, fast warming of the surface layer and weak wind-induced mixing in spring resulted in strong vertical stratification. The peak of the spring bloom, which generates most of the sedimented organic material, is observed in the Gulf of Riga in April-May (Olli and Heiskanen, 1999; Purina et al., 2018). When the spring bloom material reaches the sediment surface, it triggers enhanced oxygen consumption, with the rate and delay depending on the bloom species composition, e.g., diatom-dinoflagellate ratio (Spilling et al., 2018). Aigars et al. (2015) found higher consumption rates in late spring-early summer than in late summer-autumn and related this result to the availability of organic material, i.e., settling of spring bloom. Thus, the strength of stratification in spring-early summer is a crucial factor influencing the extent of seasonal hypoxia in the Gulf of Riga and similar coastal basins. In the years with weak or absent stratification (as 2017), such a decrease in oxygen concentrations did not occur (although we could assume a similar oxygen consumption due to the settling spring bloom) since dissolved oxygen could be transported to the near-bottom layer from the upper water layers.

Although strong stratification is a major factor in hypoxia development, we suggest that the oxygen consumption rate in the NBL of the Gulf of Riga is high enough to lead to hypoxia even if stratification at its peak is not very strong. 2015 is an example year

~~with relatively weak stratification and detected hypoxia – the stratified period was long enough for hypoxia to develop in late October but not earlier. The opposite situation was depicted in 2016 – vertical stratification was among the strongest but hypoxia was not detected since the water column was fully mixed before the autumn monitoring cruise in late October. We suggest that a longer duration of the stratified season in recent years, as also revealed by other authors, e.g., Wasmund et al. (2019), has increased the probability of hypoxia occurrences in the near-bottom layer of seasonally stratified coastal basins in autumn. The latter could have caused the observed sharp decline in near-bottom oxygen concentrations in the Gulf of Riga in autumn (but not in summer) during the last 15 years.~~

~~In April 2018, we observed vertical salinity and dissolved oxygen gradients in the deep layer. The appearance of the saltier near-bottom layer matches with the observed easterly winds in February-March 2018, which could create the inflows of Baltic Proper waters through the Irbe Strait (Lips et al., 1995; Raudsepp and Elken, 1995). A similar thin near-bottom layer with higher salinity was observed in spring 2014, and in both years, the oxygen depletion was the deepest in summer compared to the other years. The year 2018 was specific since additional inflows of saltier waters in early summer caused an uplift of the already low oxygen near-bottom waters. As a consequence, the border of hypoxic waters was at its shallowest depth, and the estimated extent of hypoxic bottoms was the largest. No further inflows in summer 2014 resulted in the lowest oxygen concentration in the NBL in 2014, and further inflows in September 2013 led to NBL oxygenation and no hypoxia in October 2013.~~

~~To answer the formulated questions, we can state that, in general, the year 2018 was in agreement with the long-term changes in the GoR oxygen dynamics – near-bottom hypoxia is developed more frequently in recent years than earlier. On the other hand, the largest extent of hypoxia was a result of the rapid warming of the surface layer and strengthening of thermal stratification and a specific sequence of inflows in spring-early summer (creating deep pycnocline) and the absence of inflows since August. Additionally, high freshwater inputs in autumn-winter 2017-2018 could bring more organic matter into the system. We further analyzed how the climate change projections could influence these factors and thus the occurrence of hypoxia in the GoR.~~

Earlier ~~modelling~~modeling studies have stated that possible future changes in climate, including warming that causes the strengthening of stratification and decreased oxygen solubility, and changes in precipitation/river runoff, influence the extent of hypoxia in the Baltic Sea (Meier et al., 2011). Strengthening of vertical stratification is predicted by the projected future increase in sea surface temperatures (Gröger et al., 2019; Meier and Saraiva, 2020; Saraiva et al., 2019b). Also, an increase in the total runoff to the Baltic Sea is predicted (Saraiva et al., 2019a, 2019b) that could lead to a decrease in surface salinity, but these predictions are uncertain. Although climate projections for wind are uncertain in the Baltic Sea area (Christensen et al., 2015), a slight decrease in wind speed in spring is expected (Ruosteenoja et al., 2019). ~~Low~~Lower wind speed ~~leads to low~~reduces vertical mixing and ~~strong~~enhances stratification. Thus, in general, the future projections seem to ~~be in~~ favor ~~of~~ a strengthened stratification regime. ~~Furthermore, weaker winds in spring create more favorable conditions for a steady outflow in the surface layer and inflow in the sub-surface layer through the Irbe Strait.~~ When also considering a predicted winter river runoff increase due to intermittent melting (Stonevičius et al., 2017)~~ – which would potentially bring additional nutrients to the sea~~ – which would potentially bring additional nutrients and organic matter to the sea (Yurkovskis, 2004) – hypoxic events in the future would probably occur more often and perhaps be even more severe.

Although phosphorus inputs into the Gulf of Riga have decreased (HELCOM, 2018b), they are still higher than ~~maximum allowable inputs by about 1000 t year^{-1} (HELCOM, 2019).~~the maximum allowable inputs by about 1000 t year^{-1} (HELCOM, 2022). Our analysis of the long-term nutrient data revealed a statistically significant increasing trend in near-bottom phosphate and total phosphorus concentrations in the stratified season. A ~~positive~~negative correlation between the near-bottom phosphate and oxygen concentrations points to the internal load – the release of phosphates from the bottom sediments under low oxygen concentrations

~~(e.g. Pitkänen et al., 2001). Using an indirect method suggested in this study, the estimated phosphate fluxes reached up to 13.5 µmol m^{-2} h^{-1} from the end of May to mid-July 2018. The observed increase in phosphate concentrations in the NBL in summer 2018 already before hypoxia development~~(van Helmond et al., 2020; Pitkänen et al., 2001). ~~agrees with the results by Aigars et al. (2015), showing that the phosphate flux did increase substantially at oxygen concentration <6 mg l^{-1}.~~

~~Earlier studies by Eglīte et al. (2014) and Aigars et al. (2015) have obtained similar estimates of the sediment phosphorus release. The average phosphate fluxes directed out of the sediments obtained by Eglīte et al. (2014) varied between 4.8 µmol m^{-2} h^{-1} at low oxygen concentrations (1-2 mg l^{-1}) and 1.8 µmol m^{-2} h^{-1} at 10 mg l^{-1}. Aigars et al. (2015) found that the average phosphate fluxes from sediments gradually increased from low values 2-5 µmol m^{-2} h^{-1} in April-May to 55 µmol m^{-2} h^{-1} in October 2012. Our~~
10 ~~maximum flux estimates from late May to mid-July are close to the values obtained by Aigars et al. (2015) in June-August, but we did not observe a further increase of NBL phosphate concentrations in late summer-autumn. The sediment flux of phosphates obtained in this study also agrees with an average estimate for the coastal Gulf of Finland — 13 kg km^{-2} d^{-1} or 17 µmol m^{-2} h^{-1} (Pitkänen et al., 2001).~~

15 ~~We showed that the meteorological and hydrological conditions highly influence hypoxia development, and the internal load of phosphorus is linked to near-bottom oxygen conditions.~~ This result agrees with other studies based on long-term monitoring and targeted research data stating that the phosphorus dynamics in the ~~Gulf of Finland~~Baltic Sea basins is ~~also~~ largely defined by the meteorological and hydrographic conditions (Lehtoranta et al., 2017; Lips et al., 2017). ~~In the Baltic Sea scale, such~~Such internal ~~load of~~ phosphorus load also supports cyanobacterial nitrogen fixation and, thus, counteracts not only external phosphorus load
20 reduction but also external nitrogen load reduction (Savchuk, 2018).

Based on the indirect method suggested in this study, the estimated phosphate fluxes from sediments reached up to 13.5 µmol m^{-2} h^{-1} from the end of May to mid-July 2018. This estimate agrees with the earlier studies in the Gulf of Riga by Eglīte et al. (2014) and Aigars et al. (2015) and in the Gulf of Finland, e.g., by Pitkänen et al. (2001), who obtained a flux estimate of 13 kg km^{-2} d^{-1} or
25 17 µmol m^{-2} h^{-1}. The observed increase in phosphate concentrations in the NBL in summer 2018, already before hypoxia development, agrees with the results by Aigars et al. (2015), showing that the phosphate flux did increase substantially at oxygen concentration <6 mg l^{-1}. They also found that the average phosphate fluxes from sediments gradually increased from low values of 2-5 µmol m^{-2} h^{-1} in April-May to 55 µmol m^{-2} h^{-1} in October 2012. Our maximum flux estimates from late May to mid-July are close to the values obtained by Aigars et al. (2015) in June-August, but we did not observe a further substantial increase of NBL
30 phosphate concentrations in late summer-autumn 2018. The latter could indicate that almost all mobile phosphorus is released from the surface sediments in low oxygen conditions (e.g. Walve et al., 2018). It is difficult to suggest what has been the major factor causing the observed long-term (2005-2018) increasing trend in near-bottom phosphate concentrations – either the strengthening of stratification and prolongation of stratified season, larger phosphorus flux associated with the near-bottom inflow of saltier waters or accumulation of mobile phosphorus in the sediments. An indication of increased phosphorus flux from the Baltic Proper is the
35 revealed positive trend in phosphate concentrations in the near-bottom layer of the Irbe Strait. On the other hand, a shorter mixed season in winter could hinder the formation of Fe-oxide-bound P pool, as suggested by van Helmond et al. (2020) for similar sites in the Stockholm archipelago with relatively low mixing and low bottom water oxygen concentrations in summer.

In conclusion, we suggest that the sequence of certain processes triggered the observed extensive hypoxia in the Gulf of Riga in
40 2018. Enhanced seasonal stratification was created by the rapid warming of the surface layer and calm wind conditions in spring, leading to restricted vertical mixing. ~~In spring-early summer, inflows~~Inflows of saltier waters through the Irbe Strait in spring-early summer maintained haline stratification~~, keeping~~ in the deep layer that additionally constrained vertical mixing. Due to high respiration, hypoxia developed in the entire saltier near-bottom layer ~~relatively thin and further restricting the vertical mixing.~~

However, we showed that separated from the water layers above by the secondary pycnocline. Furthermore, the estimated average oxygen consumption rate is large enough to lead to near-bottom hypoxia also in conditions of weaker stratification but a prolonged stratified season. The projections of meteorological and hydrological conditions anticipate that the frequency and extent of hypoxia will likely increase in the future. Since the internal load of phosphorus is linked to the near-bottom oxygen conditions, this scenario also predicts no fast reduction of nutrient concentrations in the Gulf of Riga and similar coastal basins.

Data availability

Historical and forcing data can be found in databases (see Sect.2). CTD data are available via SeaDataNet. Buoy profiler data are available upon request.

Author contribution

S-TS was the main responsible person for developing methods, analyzing data, and writing the manuscript. UL and JL contributed to developing methods and writing the manuscript. TL contributed by analyzing the data and reviewing the manuscript. MS provided river inflow and Latvian CTD data and contributed to reviewing the manuscript. OS contributed by collecting and analyzing CTD data. IL contributed by analyzing the nutrient data and reviewing the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We thank the agencies and institutes funding and implementing the marine environmental monitoring programs in Estonia and Latvia. Data were provided through the Estonian environmental monitoring information system (KESE), Latvian environmental monitoring database (Latvian Environmental, Geology and Meteorology Center), HELCOM/ICES database, SeaDataNet Pan-European infrastructure for ocean and marine data management, and Copernicus Climate Change Service information. We are thankful to the crew of RV Salme and colleagues who participated in the cruises, and data exploration (Ilja Maljutenko for the help with ERA5 data). This work was supported by the Estonian Ministry of Education institutional research funding (IUT19-6), the Estonian Research Council grant (PRG602) and the joint Baltic Sea research and development program (Art 185) through Grant 03F0773A (BONUS INTEGRAL).

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