Contemporary trends in hydrophysical and hydrochemical parameters in the NE Baltic Sea

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Received 28 October 2019, accepted 23 March 2020, available online 25 April 2020

Abstract. The current study focuses on trends in hydrophysical and -chemical parameters (e.g. temperature, salinity, dissolved oxygen, chlorophyll *a* (Chl *a*), pH and nutrients) in the Estonian coastal sea and offshore areas in relation to the biogeochemical processes and marine carbon dioxide system of the Baltic Sea. Analysis of 586 time series of these parameters, retrieved during national monitoring activities in 1993–2017, revealed a number of significant trends, which characterize the changes in the northeastern (NE) Baltic Sea. The number of significant trends in the surface layer was slightly higher in the coastal sea area than in the offshore area. No significant (e.g. climate change-related) temperature trends were revealed in the surface layers of the Estonian offshore area. Over a longer time frame (since the 1970s–1980s), the trends in hydrochemical parameters have shown improved ecological conditions in the Estonian coastal waters, however, further improvement is not so obvious. In fact, most nutrient trends were positive over the last two decades. A positive Chl *a* trend was detected in the offshore area of the Baltic Proper. Dissolved oxygen trends in the bottom layers were all negative. So far, not enough parameters have been monitored for the evaluation of marine acidification processes. Several important recommendations for further improvement of monitoring programmes are suggested.

Key words: monitoring, trends, eutrophication, marine carbon dioxide system, environmental change.

INTRODUCTION

Physical and biological systems on all continents and oceans are affected by recent climate change. The most pronounced impacts of climate change can be attributed to warming, but there is also evidence of ocean acidification (Cramer et al. 2014). Monitoring studies are fundamentally important for revealing long-term changes in marine ecosystems related to anthropogenic pressure, climate change and ocean acidification (e.g. HELCOM 1988). Long-term data constitute a basis for understanding the present state of the ecosystems, a framework for assessing the severity and unusualness of the variations – to distinguish between natural variations and anthropogenically-induced changes (Sukhotin & Berger 2013).

Regional systems are highly variable and the detection of long-term trends is complicated due to fluctuations. It is essential to have high spatio-temporal data coverage for the knowledge of the natural variability of local sea. Also, as some processes result in small changes, any monitoring programme would require analytical techniques with higher accuracy and precision. A wide range of physical, chemical and biological variables contribute to coastal marine eutrophication. For example, nutrient concentrations causing eutrophication depend on the topography, and the physical and chemical properties of the coastal sea area (Kitsiou & Karydis 2011). In coastal regions, the carbon dioxide (CO_2) uptake and a decrease in seawater pH, termed as ocean acidification, may be obscured by changes resulting from a variety of different processes. Due to eutrophication, changes in the balance of primary production and respiration may mitigate marine acidification. For instance, in Chesapeake Bay in the United States, statistically significant and compelling pH trends have been attributed to increased primary production and the resulting increased respiration (Hagy et al. 2004; Waldbusser et al. 2011). The long-term pH data in Japanese coastal waters also show highly variable trends: while the general tendency is towards acidification, conspicuous spatial variations in pH trends have been found to reflect large spatial variability in the physical and chemical characteristics of coastal environments (Ishizu et al. 2019).

Climate change scenarios for the Baltic Sea predict increasing temperature and mostly also increasing precipitation during winter (Andersson et al. 2015). An increase in precipitation will result in increased nutrient input through river runoff and might cause strong eutrophication in the nearshore areas. A vast number of studies have addressed biogeochemical cycles in the Baltic Sea since the beginning of the Baltic Sea monitoring programmes (e.g. Wulff et al. 2001; Vahtera et al. 2007; Feistel et al. 2008; Gustafsson et al. 2012). More general environmental assessments of the Baltic Sea are released on a regular basis (e.g. HELCOM 1986, 2001, 2009, 2014, 2018b; Schneider et al. 2015). The latest assessment (HELCOM 2018b) reports signs of improvement, but the Baltic Sea still suffers from eutrophication. In addition, ocean acidification is considered a potential threat for the Baltic Sea. Acidification estimation is based on a long-term trend in the partial pressure of CO_2 (pCO_2) of about +2 μatm $year^{-1}$ (IPCC 2013). Omstedt et al. (2012) concluded that increased nutrient loads will not constrain future Baltic Sea acidification and all examined scenarios indicate a decrease in pH in the Baltic Sea. In order to understand long-term changes in the context of complex regional systems, interrelations between physical and biogeochemical processes, and the marine CO_2 system need to be analysed within the same framework. A considerable research effort has been made in eutrophication studies in the Baltic Sea, in recent years also in the CO_2 system and its peculiarities (Kuliński et al. 2017). The current study focuses on whether mandatory marine monitoring programmes enable sufficient evaluation of climate-induced changes, specifically in the northeastern (NE) Baltic Sea region.

The objectives of this paper were to (1) reveal trends in time series of hydrophysical and -chemical parameters in the Estonian marine area, NE Baltic Sea, (2) relate the identified trends with regional biogeochemical and marine CO_2 system processes in the Baltic Sea and (3) outline recommendations for improvements in monitoring programmes.

MATERIALS AND METHODS

Study area

The present research focuses on the coastal sea and offshore regions of Estonia in the NE Baltic Sea (Fig. 1). The study area covers the Estonian parts of the Gulf of Finland (GoF), Baltic Proper (BP) and the Gulf of Riga (GoR).

The Estonian coastal sea is relatively shallow, bordering mainland and the West Estonian Archipelago. The main influx of nutrients and pollutants takes place through this area (Astok et al. 1999). The majority of land-based nutrient load originates from diffuse sources, mainly agriculture (HELCOM 2018a), delivered to the marine environment by large rivers (the Narva, Pärnu and Kasari rivers). The major pollution point sources are associated with large coastal cities (e.g. Tallinn, Narva) and industrial enterprises (e.g. in Kohtla-Järve, NE Estonia, and in Tallinn). The pollution load decreased considerably after the construction of wastewater treatment plants in the 1990s and introduction of various water protection measures (HELCOM 2009).

The GoF is an elongated (nearly 400 km long), estuarine-like marine area in the NE part of the Baltic Sea with a surface area of 29 500 km^2. Its mean depth is 37 m, but the maximum depth exceeds 100 m in the western part of the gulf. Hydrochemical conditions are strongly influenced by saltier oxygen-poor deep waters from the BP and riverine freshwater discharge from the east. The interplay of these drivers gives rise to a salt wedge type estuarine water circulation. This wedge may be almost totally exported by strong westerly winds (Lehtoranta et al. 2017; Lips et al. 2017). The interplay of the salt- and freshwater inflow combined with the complex topography of the gulf results in a strong west–east salinity gradient and a high spatio-temporal variation in stratification (Soomere et al. 2008). During summer, the formation of a thermocline essentially eliminates vertical mixing between the upper mixed layer and deeper saltier and/or cooler waters. Convective mixing in autumn and winter breaks down the seasonal thermocline and helps to renew the water masses down to the halocline, and during stronger westerly winds down to the bottom of the GoF.

The hydrophysical conditions in the GoF largely depend on the overall conditions in the BP. The BP constitutes about half of the Baltic Sea area. Its average depth is about 55 m, but the two deepest basins reach down to 250 m (Gotland Deep) and 460 m (Landsort Deep). The water column of the central BP is permanently stratified (Feistel et al. 2008). A permanent halocline (at a depth of ~60 m) separates the less saline layer from the more saline deep water. During summer, a seasonal thermocline is formed and moves gradually down to a depth of 25–30 m. Due to the strong vertical stratification, the mixing between deep-water and upper layers is limited: bottom layers suffer from oxygen depletion (Conley et al. 2009; Carstensen et al. 2014) and an increase in hydrogen sulphide (H_2S) areas (Feistel et al. 2016; Hansson et al. 2018).

The GoR (surface area 17 913 km^2, average depth 26 m) is a transition zone between the nutrient-rich water from several large rivers and saltier BP waters. This relatively shallow sub-basin is connected to the BP via the Irbe and Suur straits. Water exchange between the gulf and the BP is strongly variable due to changing wind and ice cover conditions (Astok et al. 1999). The water column

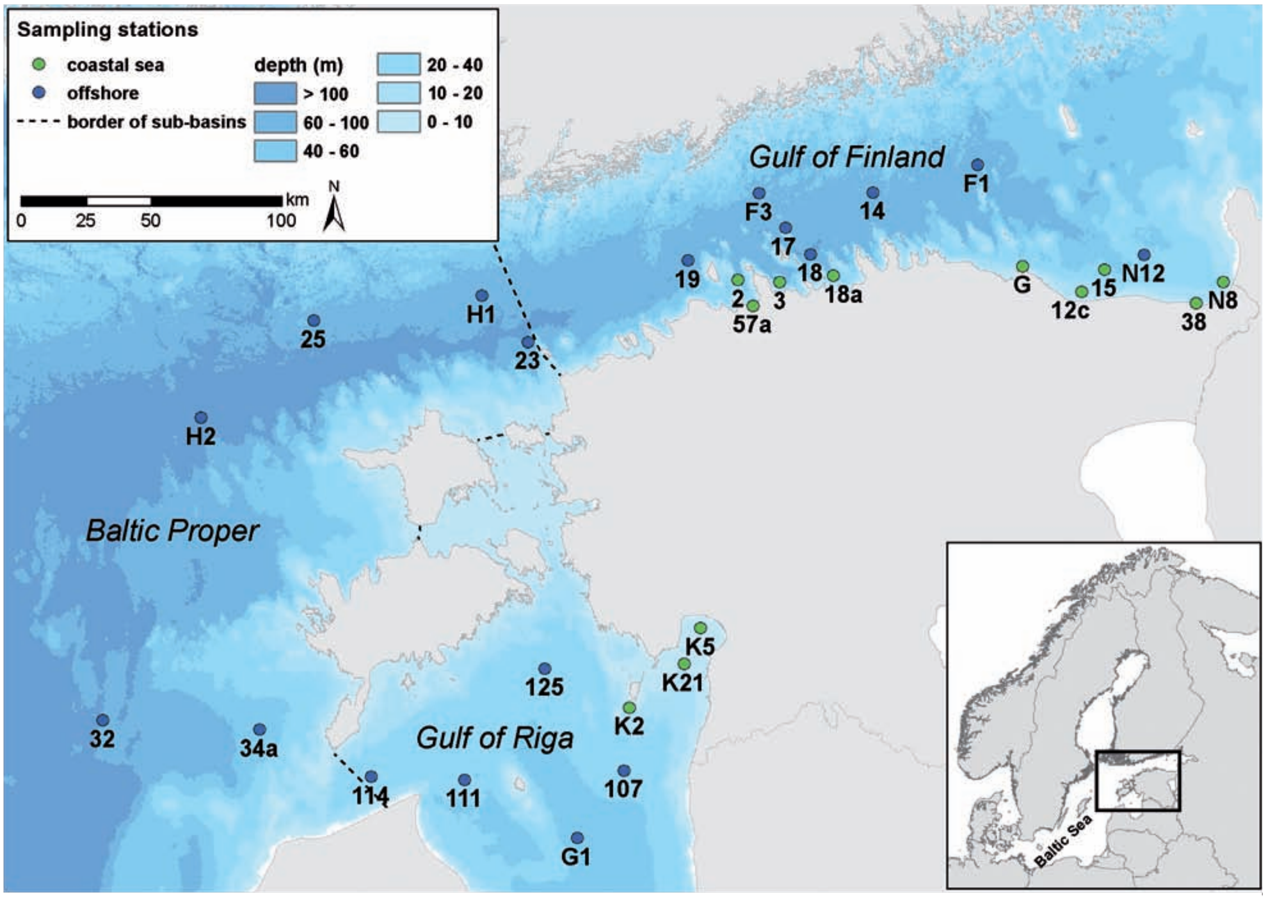

Fig. 1. Study area and monitoring stations (Table 1). The depth map layer by Baltic Sea Hydrographic Commission (2013).

is thermally stratified during summer but vertically mixed during winter (Skudra & Lips 2017). The permanent halocline of the BP does not reach the gulf (Liblik et al. 2017). The rivers entering the gulf deliver large amounts of nutrients, resulting in concentrations of nitrogen and phosphorus approximately twice as high as in the BP (Suursaar & Kullas 2016).

Historical overview of Estonian monitoring activities

Historically, the Baltic Sea has been monitored according to the requirements of different national programmes and at several organizational levels. Attempts to unify such efforts were started by the Helsinki Commission (HELCOM) in 1979, and subsequently, the first joint activities, including the Baltic Monitoring Programme (BMP) were initiated (HELCOM 1986). For Estonia, it took a decade to harmonize hydrochemical sampling and analytical methods with the international standards.

Regular measurements of hydrological and hydrochemical parameters have been carried out along the coast of Estonia since 1968. Until 1991, these observations were conducted within the monitoring system of the former Union of Soviet Socialist Republics (USSR), at 40–50 stations and approximately 3–6 times during the ice-free period. The parameters measured included water temperature, salinity, dissolved oxygen, pH, ammonium (N_{NH4}), nitrite (N_{NO2}), nitrate (N_{NO3}) and phosphate (P_{PO4}). From 1984, total phosphorus (P_{tot}), silicate (Si_{SiO4}) and to a lesser extent total nitrogen (N_{tot}) were also included. The monitoring data for the Estonian coastal sea area was digitized and statistically analysed at the beginning of the 1990s (Suursaar 1992). Evaluation and comparison between international (BMP based) and national (USSR standards based) data sets revealed frequent incompatibility due to different sampling and analysis standards (Suursaar 1994).

Following the disintegration of the USSR in 1991, a radical revision of the Estonian national monitoring began. Since 1993, marine monitoring in Estonia has been conducted by the Estonian Marine Institute, University of Tartu (since 2010 offshore monitoring has been conducted in cooperation with the Department of Marine Systems, Tallinn University of Technology). The present programme is based on the requirements of the BMP, the new Baltic Sea Programme from 1988 guidelines (HELCOM 1988) and the European Water Framework Directive. The data are routinely forwarded to the International Council for the Exploration of the Sea (ICES) oceanographic database and used in regional assessments (e.g. HELCOM 2001, 2009, 2014, 2018b; Kaukver 2015; Schneider et al. 2015). In this study we use the monitoring data from 1993–2017 with a few references to the data collected before 1993.

Sampling routines and analytical methods

We employed data from 30 different stations selected according to data availability. We used data sets with the longest time series and best available seasonal sampling frequency. The selected stations were partitioned into the three sub-basins (GoF, BP and GoR) and subdivided into the coastal sea and offshore areas (12 and 18 stations, respectively), following the baseline definition of the European Water Framework Directive (Fig. 1; Table 1). As no time series of sufficient length exist for the BP coastal sea area, in the BP only the data from offshore stations were taken into account. In total, the dataset consisted of nearly 20 000 samples measured over 25 years.

For trend assessment, intra-annually, the data were analysed in two periods: winter (December to February) and summer (June to September). The availability of data differed between the months and years (Fig. 2). Poor representation of winter months was mainly due to economic reasons and the monitoring programme of the specific year, as well as the adverse nautical conditions (ice cover) and low indicative values of some biological parameters (e.g. chlorophyll) during winter. Therefore, the first decade of the 2000s was treated with caution in the trend analysis due to the scarcity of available data. However, large amounts of data and good agreement between stations made it possible to reveal long-term trends in the individual areas (GoF, BP, GoR).

According to the Estonian national monitoring plan, samples were taken from depths of 1, 5 and 10 m, and from the bottom water. The surface layer was defined as the mean of the upper 0–10 m (i.e. the data of samples from 1, 5 and 10 m were averaged), which is the depth range where most of the primary production occurs. The bottom layer was defined as the near-bottom water layer below the halocline and considered only for the GoF and BP deep offshore stations (Table 1; stations indicated in bold). The evaluated hydrophysical and -chemical variables were water temperature, salinity, dissolved oxygen, H_2S, chlorophyll *a* (Chl *a*), transparency (Secchi disc depth), pH and nutrients (N_{NH4}, $N_{NO2+NO3} = N_{NOx}$, P_{PO4}, Si_{SiO4}, N_{tot}, P_{tot}). From the variety of marine CO_2 system parameters only pH was included in the Estonian national monitoring programme. All measurements followed the Guidelines for the Baltic Monitoring Programme (HELCOM 1988) and, from 1998, the HELCOM COMBINE manual (HELCOM 2017), which is updated more or less annually, most recently in 2017.

Temperature and salinity were measured with conductivity–temperature–depth (CTD) profilers. The practical salinities were converted to absolute salinity according to The International Thermodynamic Equation of Seawater – 2010 (McDougall et al. 2012). The dissolved oxygen concentration at coastal stations was measured using either sensors integrated with CTD profilers or with dissolved oxygen meters. At the offshore stations, oxygen concentration was determined directly after sampling by the electrochemical method (Grasshoff et al. 1983, 1999). The concentration of H_2S was measured by titration (Grasshoff et al. 1999). The Chl *a* concentration within a sample was determined optically by spectrophotometry (light absorption) (HELCOM 1988; ISO 1992). The pH value was determined potentiometrically on the NBS/IUPAC scale (Grasshoff et al. 1983, 1999; ISO 1994, 2008). The concentrations of N_{NH4}, N_{NOx}, P_{PO4}, Si_{SiO4}, N_{tot} and P_{tot} were found by manual or automated chemical treatment (continuous flow analyser) and by spectrophotometric detection (Grasshoff et al. 1983, 1999). Dissolved inorganic nutrient (N_{NH4}, N_{NOx}, P_{PO4}, Si_{SiO4}) concentrations were not evaluated in the surface layer during summer periods because the concentrations observed were often below limits of detection due to biological activity. Total nutrient (N_{tot}, P_{tot}) concentrations were evaluated during winter and summer.

To describe temporal variability in long time series (1970–2017) and evaluate the persistency of the revealed trends, data from the monitoring stations at the entrance of the GoF (around 59.5°N, 22.9°E; mean depth of stations 85 m) were used. The near-bottom water layer below the halocline where seasonality has relatively low influence was selected for analysis. As the sampling procedure and analytical methods varied over the time period of 1970–2017, some variables estimated during the two historic sub-periods (USSR and independent Estonia) are not directly comparable (Suursaar 1994). Therefore, only a few, relatively consistent long-term time series (temperature, salinity, oxygen and pH) were studied in this work.

Statistical analysis

To ensure that the studied stations cover the same time span, the sampling time frames were overviewed by station, year, season, water layer and parameter (Figs 3, 4). The Mann–Kendall test was used to identify trends in time series of the measured parameters. Time series were formed separately for each station, season, water layer and

Table 1. List of coastal sea and offshore stations with their respective standard depths. The stations indicated in bold were included in the bottom layer analysis

Sea area	Station	Coastal sea/ offshore area	Latitude N	Longitude E	Standard depth (m)
GoF	57a	Coastal sea	59.4500	24.7883	8
GoF	2	Coastal sea	59.5392	24.6864	45
GoF	3	Coastal sea	59.5298	24.9701	36
GoF	18a	Coastal sea	59.5500	25.3333	44
GoF	G	Coastal sea	59.5633	26.6233	9
GoF	12c	Coastal sea	59.4667	27.0167	12
GoF	15	Coastal sea	59.5400	27.1750	24
GoF	38	Coastal sea	59.4067	27.7833	9
GoF	N8	Coastal sea	59.4748	27.9764	18
GoF	N12	Offshore area	59.5833	27.4500	37
GoF	**F1**	**Offshore area**	**59.9167**	**26.3417**	**82**
GoF	**14**	**Offshore area**	**59.8333**	**25.6167**	**75**
GoF	**18**	**Offshore area**	**59.6250**	**25.1833**	**99**
GoF	**17**	**Offshore area**	**59.7167**	**25.0167**	**108**
GoF	**F3**	**Offshore area**	**59.8383**	**24.8383**	**80**
GoF	**19**	**Offshore area**	**59.6083**	**24.3500**	**83**
BP	**23**	**Offshore area**	**59.3250**	**23.2667**	**95**
BP	**H1**	**Offshore area**	**59.4833**	**22.9500**	**80**
BP	**25**	**Offshore area**	**59.3833**	**21.8167**	**80**
BP	**H2**	**Offshore area**	**59.0333**	**21.0833**	**173**
BP	**32**	**Offshore area**	**57.9750**	**20.5333**	**98**
BP	34a	Offshore area	57.9667	21.5500	50
GoR	K2	Coastal sea	58.0667	23.9533	12
GoR	K21	Coastal sea	58.2167	24.3083	12
GoR	K5	Coastal sea	58.3396	24.4188	5
GoR	114	Offshore area	57.8167	22.2833	30
GoR	111	Offshore area	57.8133	22.8883	39
GoR	G1	Offshore area	57.6167	23.6167	54
GoR	107	Offshore area	57.8500	23.9167	31
GoR	125	Offshore area	58.2000	23.4000	28

hydrophysical and -chemical parameter. The hydrophysical and -chemical parameter values within an individual season of a year were averaged. The Mann–Kendall test is a nonparametric test for monotonic trends which has been widely used to detect trends in time series of environmental, hydrological and climate data (e.g. Libiseller & Grimvall 2002; Hipel & McLeod 2005; Hamed 2008). The tests were performed using the package trend (Pohlert 2018) in the statistical software R 3.4.3 (R Core Team 2017) and were run separately for each station, season, water layer and hydrophysical and -chemical parameter. The tests resulted in numeric estimates of statistical significance (in terms of so-called *p*-values) and Kendall's tau coefficient (τ). Kendall's tau is a measure of correlation and takes the values between minus one and plus one where negative values indicate decreasing trends and positive values increasing trends. It was possible to extract 586 time series that had more than

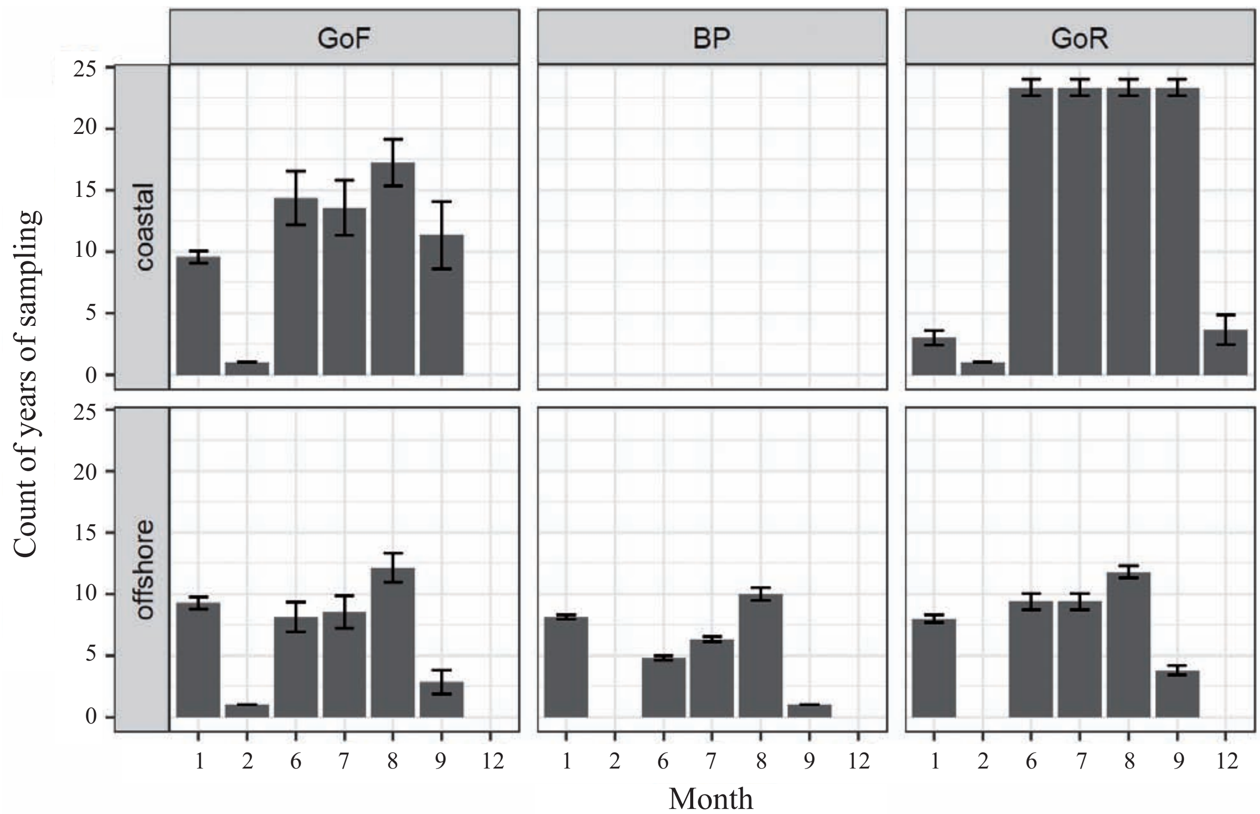

Fig. 2. Sampling frequency: monthly distribution of samplings (years) averaged over an area. Error bars indicate variabilities expressed as standard deviations.

eight years of measurements. Eight years were selected to cover also the shorter period of winter monitoring. Mean *τ* and *p* values for each sea area, season, water layer and parameter combination were visualized using bar plots (Figs 5, 6).

For the long time series (1970–2017), linear regression was used to provide information on the data scatter, as well as on the possible change of trend over time. Temperature, salinity, oxygen and pH time series were constructed. The linear trendlines for two sub-periods (i.e. USSR in 1970–1992 and independent Estonia in 1993–2017) were drawn using the least-squares method.

RESULTS

Summary statistics on hydrophysical and -chemical parameters

Seasonal mean values and standard deviations of the variables per sub-basin are presented in Table 2. For the reasons described in the previous section, the coastal sea area only included data from the GoF and GoR surface layers. The bottom layer was considered in the deep-water stations in the GoF and BP.

The GoF coastal sea area was slightly colder, more saline and less turbid (i.e., with higher Secchi depth values) than the similar area in the GoR. It had lower Chl *a* and nutrient values (Table 2). The most marked, two- to three-fold differences between the two areas occurred in winter concentrations of nitrogen compounds. The differences in the properties of water in the offshore surface areas of the same sub-basins were much smaller. Also, the variability in the offshore areas was lower than in the coastal sea areas.

Oxygen concentrations were lower in the offshore bottom layer of the BP than in the GoF both in summer and winter (Table 2). This difference is also reflected in related biogeochemical processes (higher N_{NH4} concentrations; lower N_{NO3} concentrations; higher P_{PO4} concentrations).

Seasonal differences were profound in all sub-basins and in most of the parameters, especially in temperature, Chl *a* and nutrients. However, seasonal variations were much smaller in the bottom layer than in the surface layer. Salinity values were consistently higher in the bottom layer than in the surface layer, whereas oxygen concentrations (accompanied by occasional appearance of H_2S) and average pH values were lower. Bottom layer nutrient concentrations differed from those in the surface

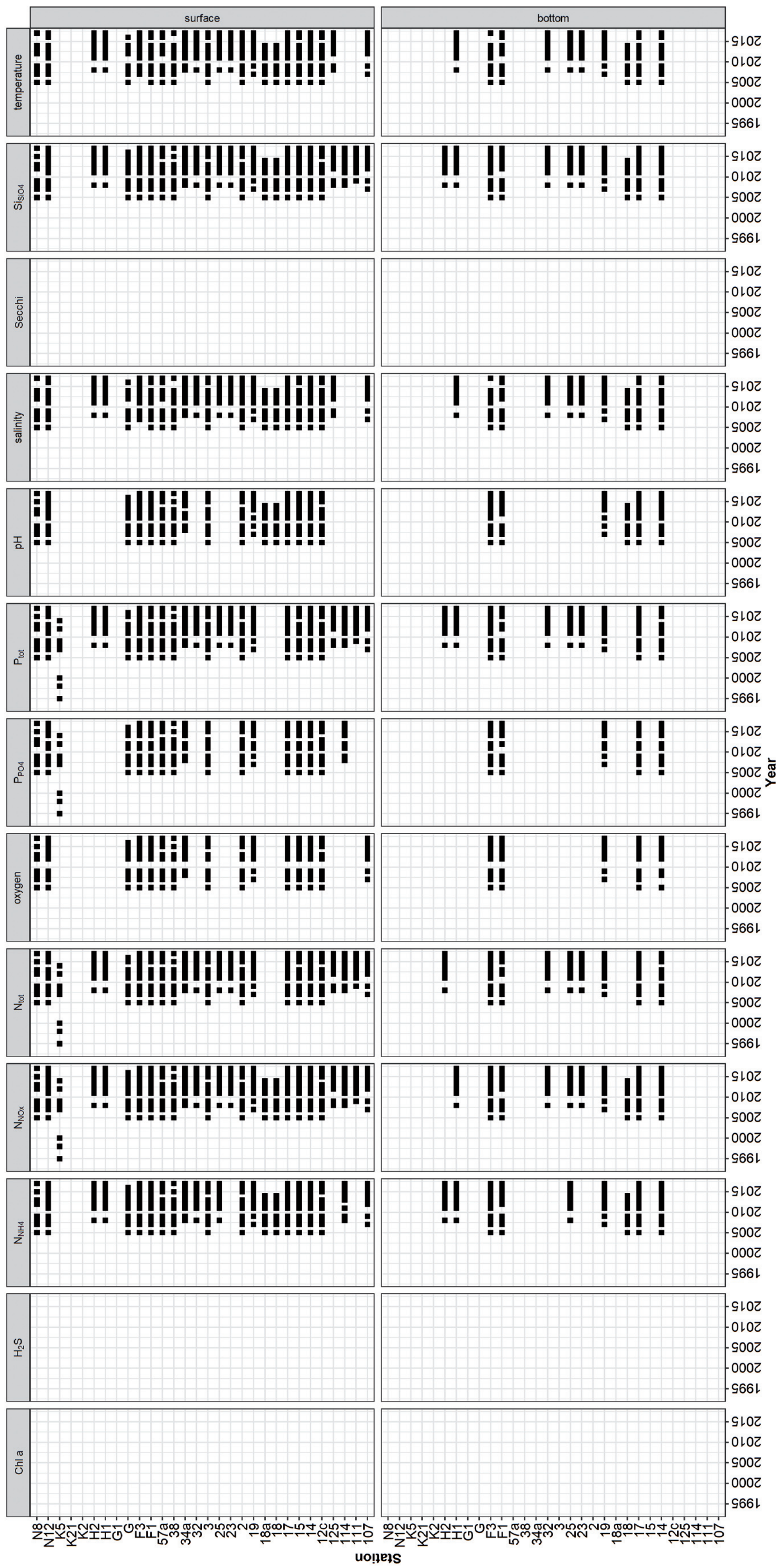

Fig. 3. Sampling time frames of the sampling stations by each water layer and variable combination in the winter seasons of 1993–2017.

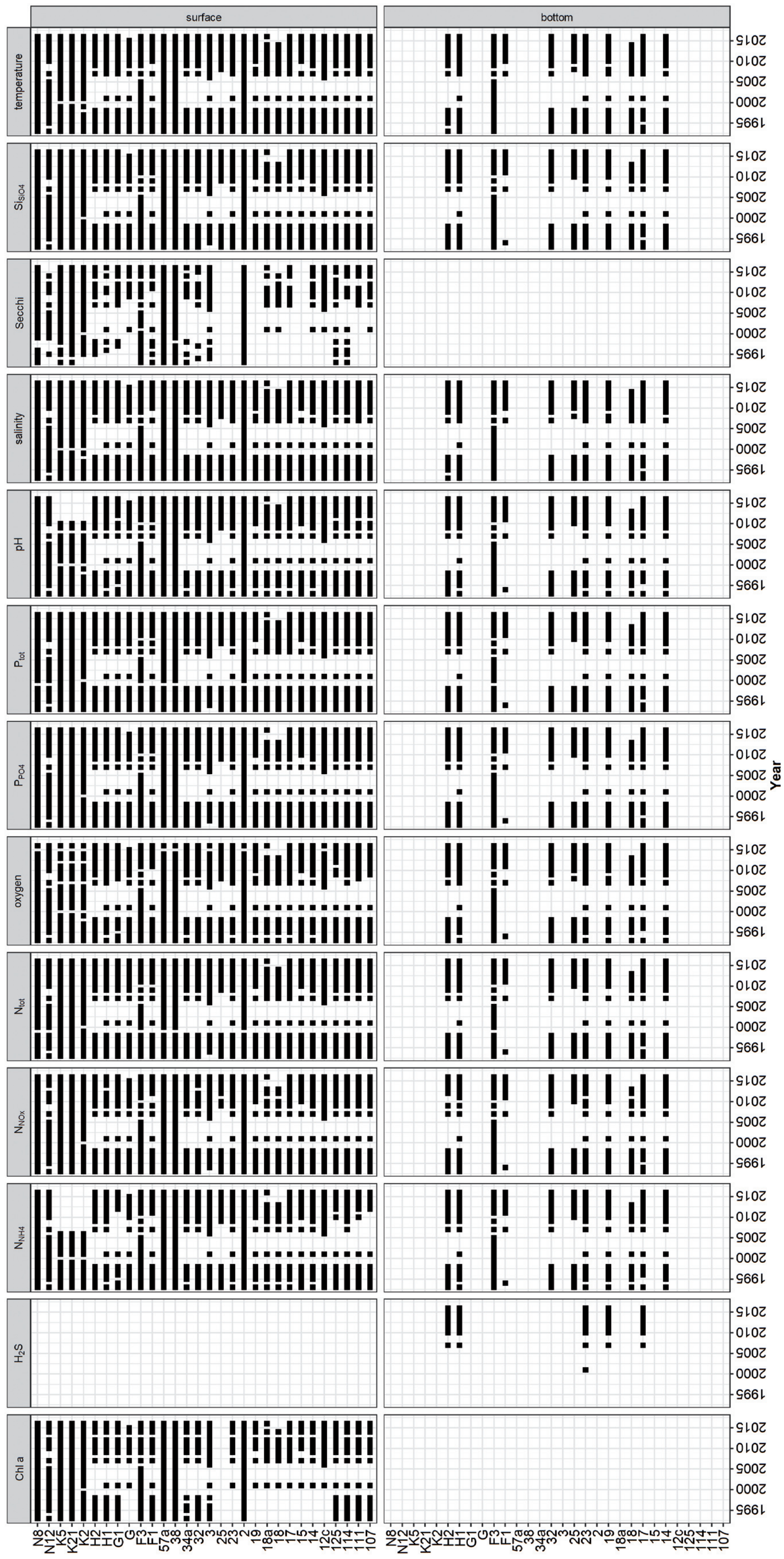

Fig. 4. Sampling time frames of the sampling stations by each water layer and variable combination in the summer seasons of 1993–2017.

Table 2. Seasonal (winter: December to February; summer: June to September) mean values of hydrophysical and -chemical parameters in different sea areas during 1993–2017. Standard deviation (SD) is shown in brackets; below LoD – below limit of detection. The sections marked with grey background were not evaluated

	Parameter	Gulf of Finland		Baltic Proper		Gulf of Riga	
		Winter (±SD)	Summer (±SD)	Winter (±SD)	Summer (±SD)	Winter (±SD)	Summer (±SD)
Coastal sea area, Surface layer	Temperature (°C)	1.83 (±1.11)	14.92 (±4.07)			2.32 (±1.53)	17.17 (±3.47)
	Salinity (g kg^{-1})	5.57 (±0.64)	4.92 (±0.96)			4.79 (±0.84)	5.00 (±0.68)
	Oxygen (mL L^{-1})	8.45 (±0.60)	6.88 (±1.19)			9.43 (±2.21)	6.19 (±1.17)
	Chl *a* (µg L^{-1})	0.8 (±0.32)	4.6 (±2.81)			2.6 (±0.91)	4.9 (±2.89)
	Secchi (m)	3.6 (±1.77)	3.8 (±1.39)			1.0 (±0.66)	1.9 (±0.97)
	pH	7.97 (±0.13)	8.30 (±0.31)			8.09 (±0.12)	8.21 (±0.27)
	N_{NH4} (µmolN L^{-1})	0.26 (±0.25)	Below LoD			0.86 (±0.81)	Below LoD
	N_{NOx} (µmolN L^{-1})	6.52 (±2.29)	Below LoD			19.58 (±15.71)	Below LoD
	N_{tot} (µmolN L^{-1})	19.88 (±6.43)	22.80 (±7.47)			52.29 (±29.32)	32.58 (±10.56)
	P_{PO4} (µmolP L^{-1})	0.91 (±0.32)	Below LoD			1.23 (±1.26)	Below LoD
	P_{tot} (µmolP L^{-1})	1.25 (±0.4)	0.82 (±0.41)			1.99 (±1.76)	1.04 (±0.66)
	Si_{SiO4} (µmolSi L^{-1})	13.12 (±6.19)	Below LoD			19.80 (±9.75)	Below LoD
Offshore area, Surface layer	Temperature (°C)	2.39 (±1.17)	15.38 (±3.61)	3.94 (±1.24)	15.56 (±3.57)	2.27 (±1.30)	15.88 (±3.54)
	Salinity (g kg^{-1})	5.74 (±0.50)	5.02 (±0.64)	6.90 (±0.30)	6.39 (±0.39)	5.71 (±0.25)	5.45 (±0.59)
	Oxygen (mL L^{-1})	8.29 (±0.64)	7.15 (±1.01)	8.04 (±0.34)	7.10 (±0.89)	8.47 (±0.36)	6.89 (±1.06)
	Chl *a* (µg L^{-1})	0.9 (±0.33)	3.8 (±1.68)	0.5 (±0.24)	3.2 (±1.50)	1.8 (±0.8)	3.3 (±1.83)
	Secchi (m)	5.8 (±1.2)	4.5 (±1.11)	9.2 (±3.32)	5.2 (±1.46)	2.6 (±0.95)	3.8 (±0.8)
	pH	7.96 (±0.12)	8.48 (±0.25)	8.01 (±0.10)	8.40 (±0.13)	8.11 (±0.09)	8.50 (±0.23)
	N_{NH4} (µmolN L^{-1})	0.15 (±0.08)	Below LoD	0.28 (±0.27)	Below LoD	0.20 (±0.11)	Below LoD
	N_{NOx} (µmolN L^{-1})	5.88 (±2.14)	Below LoD	4.39 (±1.59)	Below LoD	9.22 (±3.48)	Below LoD
	N_{tot} (µmolN L^{-1})	20.41 (±6.28)	20.22 (±5.00)	20.10 (±3.82)	18.83 (±4.84)	27.64 (±6.04)	28.53 (±20.92)
	P_{PO4} (µmolP L^{-1})	0.92 (±0.32)	Below LoD	0.73 (±0.22)	Below LoD	0.96 (±0.38)	Below LoD
	P_{tot} (µmolP L^{-1})	1.25 (±0.40)	0.74 (±0.42)	1.22 (±0.55)	0.68 (±0.61)	1.49 (±0.53)	0.82 (±0.49)
	Si_{SiO4} (µmolSi L^{-1})	12.94 (±5.70)	Below LoD	10.76 (±3.78)	Below LoD	19.69 (±7.15)	Below LoD
Offshore area, Bottom layer	Temperature (°C)	5.02 (±0.70)	4.34 (±0.74)	5.52 (±0.46)	5.12 (±0.72)		
	Salinity (g kg^{-1})	7.39 (±1.13)	8.94 (±0.83)	9.70 (±1.38)	10.02 (±0.99)		
	Oxygen (mL L^{-1})	5.19 (±2.49)	2.02 (±1.89)	2.05 (±2.58)	1.11 (±1.62)		
	H_2S (mg L^{-1})	0.05 (±0.03)	0.45 (±0.40)	0.42 (±0.32)	0.73 (±0.37)		
	pH	7.65 (±0.27)	7.33 (±0.18)	7.41 (±0.27)	7.26 (±0.13)		
	N_{NH4} (µmolN L^{-1})	1.07 (±1.74)	3.14 (±3.22)	3.54 (±2.81)	4.49 (±3.55)		
	N_{NOx} (µmolN L^{-1})	5.21 (±2.17)	4.05 (±3.07)	2.66 (±2.38)	2.02 (±2.28)		
	N_{tot} (µmolN L^{-1})	19.33 (±6.05)	20.76 (±5.68)	20.22 (±3.91)	19.7 (±7.02)		
	P_{PO4} (µmolP L^{-1})	1.61 (±0.91)	3.14 (±1.66)	2.92 (±1.28)	2.99 (±1.44)		
	P_{tot} (µmolP L^{-1})	2.14 (±1.16)	3.80 (±1.85)	3.51 (±1.34)	3.67 (±1.77)		
	Si_{SiO4} (µmolSi L^{-1})	20.45 (±11.14)	34.10 (±14.32)	33.22 (±12.72)	34.69 (±17.60)		

layer. The difference was more pronounced in the data reflecting inorganic nutrients.

Detected trends

In the time frame of 1993–2017, only 27% out of the total number of 586 time series had statistically significant trends ($p < 0.05$) (Table 3). The proportion of significant trends was the highest in the BP (33%) and the lowest in the GoR (12%). The number of significant trends was slightly larger in the parameters measured in the coastal sea surface layer (20%) compared to the offshore surface layer (16%). The proportion of statistically significant trends was higher in the bottom (46%) than in the surface layer (16%). The number of statistically significant trends was larger in summer than in winter.

The mean strength (τ) and statistical significance (p) of trends for each sea area, season, water layer and parameter are visualized in Figs 5 and 6. No statistically significant ($p < 0.05$) temperature trends were revealed in the surface layer. Increasing trends of temperature and salinity were prominent during summer in the bottom layer of the offshore area in the BP. A significant negative trend in dissolved oxygen concentration in the bottom layers was detected during summer in both sub-basins. A positive trend in Chl *a* was found during summertime in the BP offshore area surface layer. No significant pH trend was revealed. Regarding nutrients, in the GoF the detected significant trends were positive. Trends in the BP were similar. In the GoR coastal sea area, inversely, a negative total phosphorus trend was detected during the summer period.

The deep layers of the GoF showed a slight temperature decrease until 1990 (–0.016 °C $year^{-1}$; Fig. 7) and a clear increase of 0.061 °C $year^{-1}$ in the following decades in long time series (1970–2017). Salinity decreased (–0.13 units $year^{-1}$) in 1970–1993 and increased (0.043 units $year^{-1}$) in 1993–2017. The clear increase (0.2 mL L^{-1} per year) in oxygen concentrations changed into a decrease (–0.11 mL L^{-1} per year), whereas a gentle increasing trend in pH in the first half of the period changed into a small decrease afterwards (Fig. 7).

DISCUSSION

Trends and their interconnections with the spatio-temporal tendencies in the Baltic Sea

A total of 586 time series of temperature, salinity, oxygen, Chl *a*, pH and nutrients were performed in the framework of national marine monitoring activities. These revealed a number of significant temporal trends in the Estonian coastal sea and offshore areas between 1993 and 2017.

The Baltic Sea is composed of rather differently functioning sub-areas (e.g. Feistel et al. 2008). As in most cases the trends had the same directions in different sub-basins (Figs 5, 6), the existence of general, most likely climate-related changes in several hydrophysical and biochemical parameters can be suggested. Success in the

Table 3. Number of statistically significant ($p < 0.05$) and nonsignificant ($p \geq 0.05$) trends. Proportions of significant trends are shown in the last row and right-side columns. The sections marked with grey background were not evaluated; – no trends were revealed

		Revealed trends	Gulf of Finland		Baltic Proper		Gulf of Riga		Proportion of significant trends per water layer (%)
			Winter	Summer	Winter	Summer	Winter	Summer	
Coastal sea area	Surface layer	Significant	10	14			–	8	20
		Nonsignificant	41	65			2	22	
Offshore area	Surface layer	Significant	9	12	1	11	2	–	16
		Nonsignificant	30	47	25	34	11	40	
	Bottom layer	Significant	15	38	2	37			46
		Nonsignificant	41	26	27	16			
Proportion of significant trends per sub-basin (%)			28		33		12		

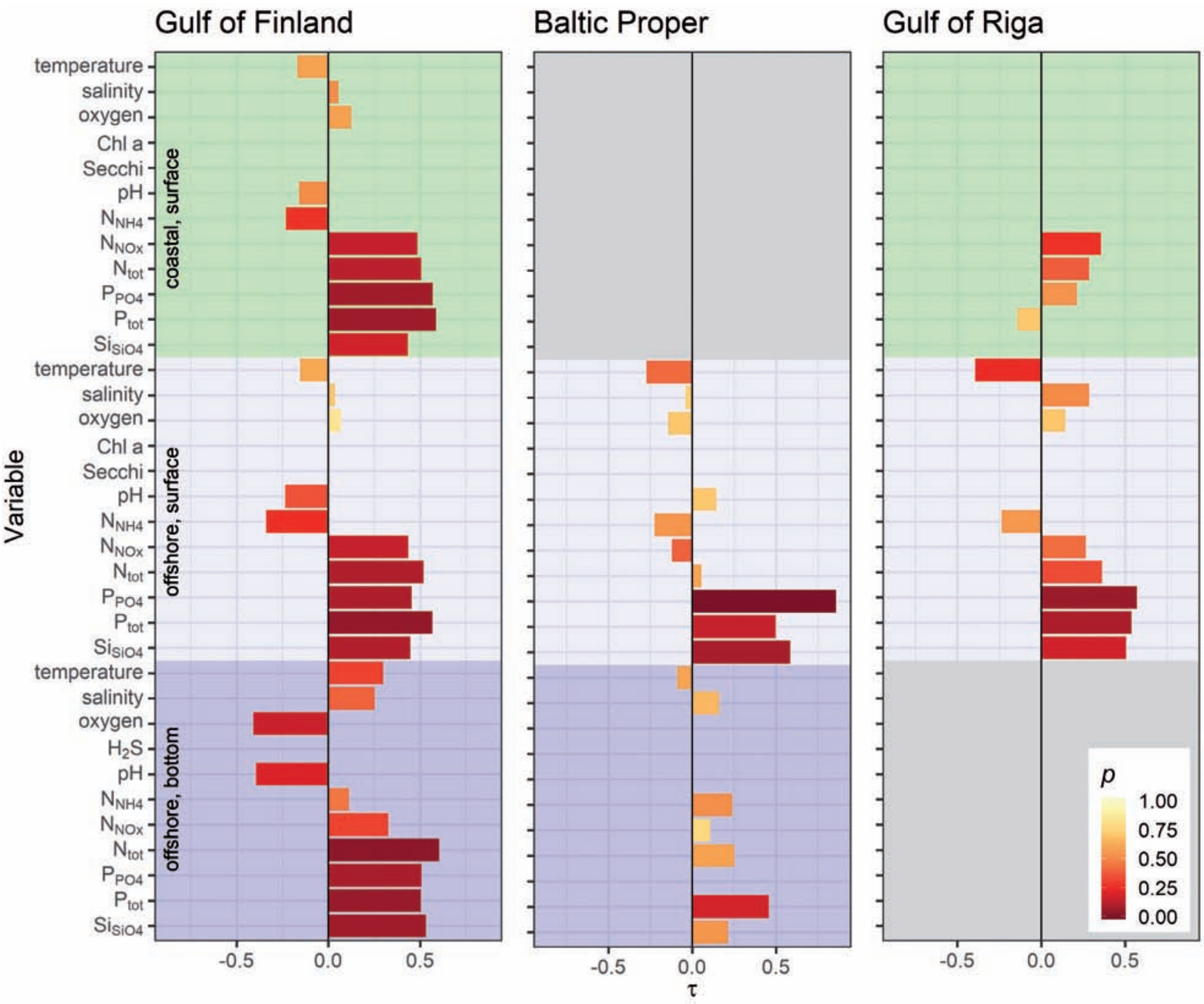

Fig. 5. Mean Kendall's tau (τ) and statistical significance (p) values during the winter seasons of 1993–2017: bar lengths indicate the mean strength (τ) of trends and colours mean statistical significance (p) of trends. Blank rows show that there were no time series available for a given sea area, water layer and variable combination. The sections marked with grey background were not included in data analysis.

detection of statistically significant trends largely depends on the variability (data scatter) within the time series (Fig. 7). In the coastal sea areas, high biological productivity and effects of seasonality increase the temporal variability of hydrophysical and -chemical parameters (Table 2) and thus may obscure the long-term trends. In the offshore areas, vertical stratification of the Baltic Sea is seasonally variable. It was deduced from the overall trend analysis that more statistically significant trends occurred in the bottom layer than in the surface layer. During the period of weak vertical stratification, the water column can be mixed down to the quasi-permanent halocline (Liblik et al. 2013). Therefore, the hydrochemical conditions in the uppermost layer may vary considerably both seasonally and inter-annually. Revealing significant trends is difficult under such circumstances. In the near-bottom and bottom layers, i.e. below the quasi-permanent halocline, the seasonality has lower influence on data variability and trends are more clearly distinguishable.

From the 1970s, the trends in several monitored parameters in the Estonian coastal sea areas apparently reflect some improvements in pollution control, possibly stipulated by the HELCOM and EU directives to all countries surrounding the Baltic Sea (e.g. HELCOM 2001; Kaukver 2015). However, spatially contrasting or positive nutrient trends revealed in this study (Figs 5, 6) do not reflect that success anymore. One can still argue that without these measures the deterioration in marine environment would have been faster and more obvious.

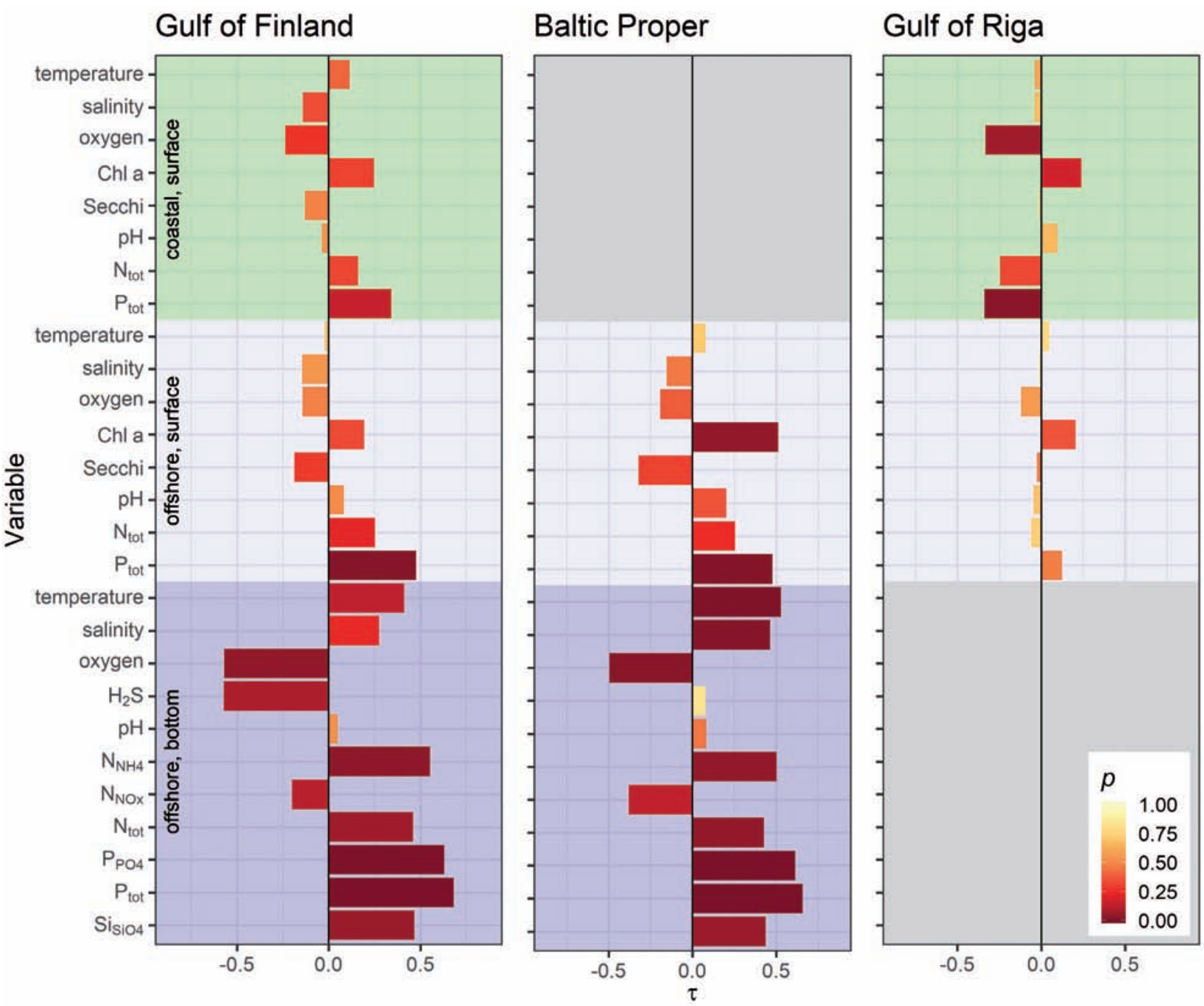

Fig. 6. Mean Kendall's tau (τ) and statistical significance (p) values during the summer seasons of 1993–2017. Notations are the same as in Fig. 5.

Trend directions were mostly similar in coastal and offshore areas, but the number of significant trends in the surface layer was slightly smaller in the offshore areas than in the coastal sea (Table 3). This feature is evident in the GoF during both seasons. The lack of winter period trends in the coastal sea of the GoR reflects the lack of the relevant data (Fig. 2). Interestingly, no statistically significant trends were revealed in the GoR offshore area in summer. Tendencies in the studied offshore areas should in principle be related to the processes in the Baltic Sea as a whole, so the revealed parameter trends are discussed in their interconnections with the spatio-temporal tendencies in the Baltic Sea.

No significant **temperature** trends were revealed in the surface layers of the Estonian marine area. Temperature has both strong seasonal and inter-annual variability (Table 2), which may obscure the possible trends. However, both air temperature and sea surface temperature have risen over the last 50 years in the Baltic Sea (e.g. Feistel et al. 2008) and a positive temperature trend occurred in 1990–2008 during summer in the surface layer of the Baltic Sea (Lehmann et al. 2011). Also, Mulet et al. (2018) show a significant increasing temperature trend (0.030 ± 0.007 °C year^{-1}) in 1993–2016. The lack of significant trends in surface layer temperature in the current study is most probably due to the scarcity in time and space of temperature data together with high variability as *in situ* measurements with higher frequency have shown sea surface temperature increase in the Baltic Sea (MacKenzie & Schiedek 2007).

In the deep layers, the long-term changes in temperature and salinity in the Baltic Sea are mainly related to the water inflows from the North Sea. Since the beginning of the 1990s, only few very strong Major Baltic

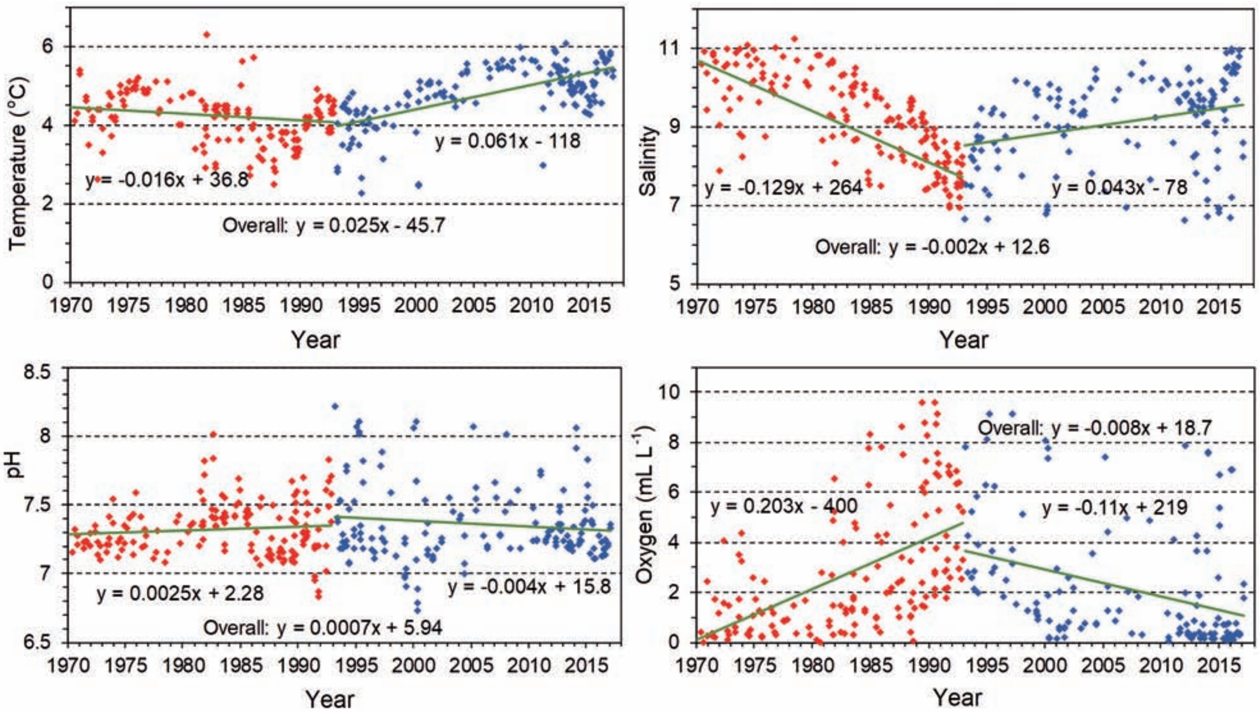

Fig. 7. Temporal course of selected hydrophysical and -chemical parameters in the bottom layer (depth 83–86 m) of the offshore Gulf of Finland during 1970–1992 (red) and the current study period 1993–2017 (blue).

Inflow (MBI) events have been recorded: in 1993 (Matthäus & Lass 1995), 2003 (Feistel et al. 2003, 2006) and several inflows from the autumn of 2014 to the beginning of 2016 (Mohrholz et al. 2015; Liblik et al. 2018). For instance, the 2014 MBI caused changes in the water column in the area from the Gotland Basin to the GoF, observed with overall increasing temperature and salinity (1 °C and 1 g kg^{-1}, respectively) in the layers below 80 m depth (Liblik et al. 2018).

The data points characterizing **salinity** in the bottom layer (Fig. 7) are somewhat scattered, most probably due to variations in the actual sampling depth, natural variations in the halocline depth and properties of local stratification (influenced by MBIs). However, the general pattern of variability in salinity time series is consistent with that reported by Liblik et al. (2018) for the Gotland and Farö deeps of the BP. They indicate how the deep layer of the GoF follows the behaviour of the central Baltic sub-halocline water mass. Salinity has increased in the bottom layer of the BP since 1993 (Fig. 6). Similarly, in the large scale, this applies also to the GoF bottom layer (Liblik & Lips 2011). No clear salinity trend in the GoR is consistent with that concluded by Skudra (2017).

Due to the lack of vertical profiles, it is not possible to evaluate the vertical extent of the negative trend in **dissolved oxygen** concentration. However, positive trends in nutrients in the surface layer indicate increased oxygen consumption in the deep layers during the mineralization process and influence on redox conditions. Additionally, the latest MBIs, when oxygenated waters have reached the Gotland Basin and pushed the former BP deep layer waters towards the GoF, have deteriorated oxygen conditions in the GoF (Fig. 5) (Liblik et al. 2018). The findings for the GoF and BP bottom layers are in line with the increasing area of oxygen-poor water in the central deep basin of the BP, reaching also into the deep basin of the GoF (Feistel et al. 2016; Hansson et al. 2018).

According to the Second HELCOM holistic assessment (HELCOM 2018b), **Chl *a*** concentrations in the Baltic Sea have remained more or less unchanged during 1990–2016. Our data revealed positive trends in Chl *a* concentrations in the BP. Considerably less Chl *a* data are available from the period 1997–2009, so the revealed trends are mainly based on the periods 1993–1998 and 2007–2017. Increase in the Chl *a* concentration in the BP has also been recorded during 1979–2000 (Wasmund & Uhlig 2003) and in the comparison of the periods 2007–2011 and 2011–2015 (HELCOM 2018b). The reason for the positive Chl *a* concentration trend in the offshore surface layers is most likely due to the N-fixing cyanobacteria blooms during summer (Vahtera et al. 2007). The magnitude of these blooms is regulated by internal processes and can be explained by positive trends in wintertime surface layer P_{PO4} (Raateoja et al. 2011) and also by bottom layer P_{tot} of previous summer: deep-water phosphorus storages are mixed throughout the water column during the autumn–winter period and fuel the primary production of the following summer.

The detected significant trends in **nutrients** were mainly positive in all sea areas with the exception of one negative trend. The external loadings of nitrogen and phosphorus have decreased significantly in recent years (HELCOM 2018a). Nevertheless, the effects of past and current nutrient inputs still largely determine the overall status, as well as the trends (Vahtera et al. 2007). A positive P_{PO4} trend was detected in the surface layer in the BP offshore area during winter. A positive total phosphorus trend was observed in the GoF. However, Raateoja et al. (2016) also indicated positive N_{NOx} and P_{PO4} trends in the GoF surface layer during the winter periods of 1996–2015. During summertime, the GoF and BP are characterized by positive P_{tot} trends. Internal processes govern the variations both in nitrogen and phosphorus concentrations. Considering nitrogen and oxygen concentrations (Table 2), denitrification is assumable in the bottom layer. Positive P_{PO4} trends most likely occurred due to release of phosphorus from the sediment in oxygen deficient conditions (Conley et al. 2002, 2009; Vahtera et al. 2007; Lehtoranta et al. 2017).

Detection of long-term **pH** trends is complicated due to two reasons: (1) considerable temporal variability of pH in the regional systems and (2) insufficient accuracy of the (potentiometric) measurement method, as well as the frequency of sampling in most areas to reveal trends in the Estonian marine area. Almén et al. (2017) revealed pH decrease in the surface and deep layers of the western part of the GoF during the winter periods of 1979–2015. A possible explanation for the deep layer was an increased level of organic material mineralization, as well as increased stratification and stagnation affecting oxygen and pCO_2. Alenius et al. (2016) claimed that the decrease in pH in the deep layer of the GoF in 1990–2010 was rather due to the strengthened stratification than due to increased atmospheric CO_2 concentration.

No other marine CO_2 system parameters than pH are currently included in the Estonian national monitoring programme. For the evaluation of marine acidification, pH measurements of higher quality and monitoring of additional three parameters are needed: pCO_2, DIC (dissolved inorganic carbon) and A_T (total alkalinity). Moreover, the observation of the marine CO_2 system is also value-adding for biogeochemical studies (e.g. organic matter production, mineralization). The estimation of organic matter production in the surface layer is generally based on nutrient depletion or oxygen production in connection with photosynthesis. Our results revealed a positive Chl *a* trend during summertime, however, the very low levels of dissolved inorganic nutrients could not be evaluated. No significant oxygen trend was revealed in the offshore surface layers. Oxygen may escape relatively quickly via gas exchange, but this was not evaluated in the current research. Measurements of pCO_2 can be used to quantify the magnitude of organic matter production and therefore complement the traditional monitoring of primary production (Schneider & Müller 2018).

In the deep layers, all oxidants need to be considered for the assessment of mineralization. So far, only measurements of dissolved oxygen and H_2S are considered, which is inadequate. As CO_2 is the primary product of mineralization, DIC concentrations reflect the progress of mineralization. At anoxic conditions, ammonia and sulphide anions are released and they have a strong effect on A_T and pH (Kuliński et al. 2017). A decrease in the bottom layer oxygen with statistically significant positive N_{NH4} trends in the offshore GoF and BP were revealed in our study. Climate projections suggest an increased spatial extent of anoxia (Meier et al. 2011, 2018), thus providing increased buffering against ocean acidification (Hjalmarsson et al. 2008; Havenhand 2012).

Evaluation of the monitoring programme and recommendations

The current research revealed some opportunities for further improvement of the national monitoring programme. Firstly, monitoring in the coastal sea areas should be conducted during the winter period as well (Fig. 2). Wintertime navigation has been problematic in the Estonian coastal waters as well as in the entire GoF. However, considering a significant (and most likely continuing) trend towards shorter ice seasons (about 20 days per hundred years; e.g. Soomere et al. 2008), some winter surveys should be added to the monitoring programme in the nearest future.

There should be at least one representative monitoring station per sub-basin where data are gathered vertically throughout the water column. It is not possible to evaluate biogeochemical processes in the water column based on the data from only the surface and bottom layers. Some of the data collected so far are not informative enough. It is recommended to re-evaluate the need for seasonal measurements of dissolved inorganic nutrients. During summer the values in the surface layer are below detection limits. It is highly recommended that in addition to the already monitored parameters, marine CO_2 system parameters (pCO_2, DIC and A_T) should be monitored with high sampling resolution (Andersson et al. 2008; Almén et al. 2017). Observations of the marine CO_2 system contribute to the biogeochemical studies, helping towards more accurate comprehension of the processes (Schneider & Müller 2018). The EU Marine Strategy Framework

Directive (MSFD 2008) stipulates the monitoring of chemical parameters such as spatial and temporal distribution of nutrients and oxygen, but also pH and pCO_2 profiles (or equivalent information aimed at quantifying marine acidification). The inclusion of carbon variables in biogeochemical models enables more accurate modelling of the concentration of organic matter. It is essential for realistic estimation of the concentration of biogeochemical variables.

Finally, a more closely integrated multi-lateral monitoring programme of the Baltic Sea sub-basins is needed, as has also been specified by the EU and HELCOM. Harmonization of high-quality analytical performance is crucial amongst the countries around the Baltic Sea.

CONCLUSIONS

A total of 586 time series were studied in the Estonian coastal sea and offshore areas in 1993–2017. In most cases the trends had the same directions in different sub-basins. The trend directions of coastal seas and offshore areas were also similar, with slightly more statistically significant trends (at a 95% level) revealed in the coastal sea areas. The number of significant trends was greater in the bottom layer than in the surface layer. As the influence of seasonality on the near-bottom layer is damped by the halocline and seasonal thermocline, detecting significant trends is more probable in bottom waters.

The trends in hydrochemical parameters in the Estonian coastal waters over a longer time frame (since the 1970s–1980s) apparently reflect improvements in the pollution control measures. However, when comparing the years 2007–2011 with 2011–2016, the integrated status assessment of eutrophication shows deteriorating conditions for the GoF, northern BP and GoR (HELCOM 2014, 2018b). Most of the significant trends in nutrient concentrations identified in this study were also positive. Additionally, a positive Chl *a* trend was detected in the offshore BP surface layer. All the dissolved oxygen trends detected in the bottom layers were negative.

The monitored parameters were not sufficient for the evaluation of marine acidification. Although Estonian long-term pH data were evaluated, no significant trends could be detected.

Several weak spots regarding the national monitoring programme were revealed. Further improvement of the monitoring programme should be encouraged. Besides pH, analysis of other CO_2 system parameters such as pCO_2, DIC and A_T is needed for the evaluation of the marine CO_2 system. These are the most informative and value-adding parameters for marine biogeochemical studies.

Acknowledgements. This study was supported by the project IUT2-20 of the Estonian Ministry of Education and Research, and the Estonian Research Council grant PUT1439. We are grateful to Arno Põllumäe for helping with the compilation of the data and all the scientists and colleagues who performed the measurements which are included in the database. We thank the referees Bo Gustafsson and Tarmo Soomere for constructive comments on the manuscript. The publication costs of this article were partially covered by the Estonian Academy of Sciences.

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Hüdrofüüsikaliste ja -keemiliste parameetrite trendid Kirde-Läänemeres

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Mere keskkonnaseisundit iseloomustavate parameetrite seirel põhinevate pikaajaliste trendide tuvastamine on eriti oluline suure muutlikkusega, haavatavates süsteemides, nagu Läänemeri. Artiklis on keskendutud hüdrofüüsikaliste ja -keemiliste parameetrite (näiteks vee temperatuur, soolsus, hapnikusisaldus, Chl *a*, pH ja toitained) trendidele Eesti ranniku- ning avameres aastail 1993–2017. Trende uuriti seoses Läänemeres asetleidvate üldisemate biogeokeemiliste ja CO_2-süsteemi protsessidega. Kokku 586 parameetri aegrea analüüsil tuvastati suur hulk statistiliselt olulisi trende, mis iseloomustavad Läänemere kirdeosa keskkonnaseisundit. Rannikult avamere suunas kahanes vähesel määral pinnavee parameetrite statistiliselt oluliste trendide osakaal. Teadaolevale kliimamuutusest põhjustatud õhu temperatuuri tõusule vaatamata olulist vee temperatuuri muutust Eesti mereala pinnakihis siiski ei tuvastatud, seda arvatavasti vähese ajalis-ruumilise katvusega andmehulga ja suhteliselt suure muutlikkuse tõttu. Eutrofeerumist kirjeldavad toitainete kontsentratsioonide trendid olid vaadeldud perioodil enamasti positiivsed (kasvavad). Ava-Läänemere kirdeosa pinnakihis kasvas Chl *a* kontsentratsioon. Vees lahustunud hapniku kontsentratsiooni trendid süvakihtides olid kõikjal negatiivsed. Leiti, et mere hapestumisprotsesside kirjeldamiseks piisab praegu jälgitavatest parameetritest. Rahvusliku mereseireprogrammi täiendamiseks esitati mitmeid soovitusi.