Oceanologia (2017) 59, 37—48

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.journals.elsevier.com/oceanologia/

ORIGINAL RESEARCH ARTICLE

Characteristics and inter-annual changes in temperature, salinity and density distribution in the Gulf of Riga

Maris Skudra [a,b,*], **Urmas Lips** [a]

[a] *Marine Systems Institute, Tallinn University of Technology, Tallinn, Estonia*
[b] *Latvian Institute of Aquatic Ecology, Riga, Latvia*

Received 12 January 2016; accepted 4 July 2016
Available online 16 July 2016

KEYWORDS
Gulf of Riga;
Temperature;
Salinity;
Vertical stratification;
Internal Rossby radius

Summary Available CTD profiles from the Gulf of Riga (May—August, 1993—2012) were analyzed to study inter-annual and long-term changes in temperature, salinity and density in relation to river runoff and atmospheric forcing (e.g. Baltic Sea Index). To describe temporal changes in vertical stratification, the upper mixed layer (UML) and deep layer (DL) parameters were estimated. On average the UML depth increases from 8.7 m in May to 9.0, 11.5 and 13.7 m in June, July and August, respectively, and the UML temperature increases from 8.0°C to 12.5, 18.7 and 18.6°C (May, June, July and August) while the UML salinity increases from 4.90 g kg^{-1} to 5.14, 5.28 and 5.38 g kg^{-1}, respectively. High correlation ($r = -0.82$) was found between the inter-annual changes in river runoff (spring) and mean salinity in the UML in August as well as between DL mean salinity ($r = 0.88$) and density ($r = 0.84$) in the Irbe Strait and DL mean salinity and density in the Gulf of Riga. Inter-annual changes in the UML depth as well as in DL salinity and density had a significant correlation with the changes in Baltic Sea Index. The strongest stratification (August) can be observed in the years with the highest UML temperature and the highest river run-off in spring. We suggest that the predicted increase in water temperature and changes in river run-off due to the climate change would result in faster development of the seasonal thermocline in spring and stronger vertical stratification in summer.

---

[*] Corresponding author at: Marine Systems Institute, Tallinn University of Technology, Akadeemia Rd. 15A, 12618 Tallinn, Estonia. Tel.: +371 28740641; fax: +372 620 4301.
E-mail address: maris.skudra@msi.ttu.ee (M. Skudra).

Peer review under the responsibility of Institute of Oceanology of the Polish Academy of Sciences.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.oceano.2016.07.001

1. Introduction

The Gulf of Riga (GoR) is a relatively closed basin in the eastern part of the Baltic Sea with surface area of 17,913 km^2 and volume 405 km^3 (Leppäranta and Myrberg, 2009). It has two openings — the Irbe Strait (sill depth of 25 m and cross-section of 0.4 km^2) in the western part and the Suur Strait (sill depth of 5 m and cross-section of 0.04 km^2) in the northern part of the gulf with 70—80% (Petrov, 1979) of the water exchange occurring through the Irbe Strait. The mean depth of the GoR is 26 m which is about two times less than in the Baltic Sea. The deepest regions of the gulf are situated to the east and southeast from Ruhnu Island where depth reaches about 56 m, although, the deepest spot in the whole GoR is Mersraga Trough (width about 50 m and length 4.5 km) with the depth of 66 m (Stiebrins and Väling, 1996) situated approximately 13 km to the north from the village of Mersrags.

The catchment area of the GoR consists of 134,000 km^2 with five major rivers discharging into the GoR — Daugava, Lielupe, Gauja, Pärnu and Salaca. First three are located in the southern part of the gulf where approximately 86% of all river run-off occurs (Berzinsh, 1995) and latter two in the eastern part. Annual mean run-off to the gulf in 1950—2012 has been stated as 1013.5 $m^3\,s^{-1}$ (Kronsell and Andersson, 2014) or approximately 32 km^3 which is about 7.9% of the volume of the gulf. It has been showed that river run-off together with the limited water exchange are the main reasons for the observed horizontal salinity difference in the surface layer — salinity decreases from the Irbe Strait to the southern part of the gulf (see e.g. Berzinsh, 1980, 1995; Stipa et al., 1999). The strongest difference can be observed in April and May when the influence of the river discharge is at its maximum and salinity decreases from about 6.0 PSU (Practical Salinity Scale) in the Irbe Strait to 2.0 PSU and less close to the mouths of Daugava and Lielupe. Slight surface salinity difference (about 1.0—1.5 PSU) can be observed also across the gulf from west to east during April (Stipa et al., 1999).

Water temperature in the GoR has a seasonal pattern — during November—February cooling of the whole water column occurs, March—April marks the start of the water column warming from surface layers which intensifies and reaches maximum during May—August and is again followed by a steady cooling during September—October. Data analysis during 1963—1990 revealed that mean temperature for the whole water column in winter, spring, summer and autumn was 0.0, 2.8, 12.0 and 9.0°C, respectively (Berzinsh, 1995). It was reported (Raudsepp, 2001) that seasonal changes in thermal stratification are consistent with the annual cycle of air-sea heat exchange. Due to these seasonal characteristics the whole water column in the GoR is thermally well mixed during December—March, whereas, seasonal thermocline starts to develop in April and the strongest stratification can be observed in August. More detailed analysis on stratification in the GoR is described in the research by Stipa et al. (1999).

According to the previous studies (Berzinsh, 1980, 1995) there have been two periods with opposite tendencies regarding salinity — from beginning of 1960s till 1977 average salinity increased (average rate of 0.035 PSU per year), whereas, from 1977 till early 1990s salinity decreased (0.041 PSU per year) which was mainly related to the dynamics of long-term river run-off. Similar decline of salinity was also observed within different layers (expressed as mean values at 0, 10, 20, 30, 40 and 50 m) of the GoR (Raudsepp, 2001). Remote sensing data for 1990—2008 has showed a strong increase of the sea surface temperature (SST) in the GoR — about 0.8—1.0°C per decade with similar or slightly higher values only in the Gulf of Finland and Bothnian Bay (BACC, 2015). Long-term changes in both, temperature and salinity, not only influence the physical characteristics of the GoR but they can have an impact to the whole ecosystem of the gulf. For example, Jurgensone et al. (2011) reported that the temperature increase would affect the phytoplankton community in the GoR suggesting a shift from dinoflagellates to chlorophytes in summer. Kotta et al. (2009) stated that the reduction in salinity had negative consequences for most of the benthic invertebrate species referring to their salinity tolerance. In general, the dynamics of zooplankton, zoobenthos and fish in the GoR primarily relies on climatic conditions.

The main goal of the present study was to describe the vertical characteristics of temperature, salinity and density fields and their inter-annual variability in the GoR based on the CTD data collected during 1993—2012 (May—August) as well as possible connection of revealed changes with different forcing factors. Previous studies have mainly focused on short-term analysis of temperature and salinity data (Kõuts and Håkansson, 1995; Stipa et al., 1999) and/or covered only the time period until 1995 (Raudsepp, 2001). In addition, present research aimed to estimate the baroclinic Rossby radius on the basis of the existing CTD profiles with a similar approach as used by Alenius et al. (2003) for the Gulf of Finland. Based on the results of this analysis and taking into account the latest climate change predictions we also suggest what could happen in the future.

2. Material and methods

Present paper analyzed the CTD data collected in 1993—2012 during various monitoring programmes and research projects conducted by Latvian Institute of Aquatic Ecology, Marine Systems Institute at Tallinn University of Technology and Institute of Food Safety, Animal Health and Environment (Latvia) and their predecessors. Vertical profiles of different parameters were acquired with following CTD profilers — AROP 500, SBE 19plus SeaCAT, SBE 19 SeaCAT, Neil Brown Mark III and Idronaut OS320plus.

In total 3558 CTD casts were processed and 863 CTD casts were used in the present study from the period of May—August, 1993—2012 with Gulf of Riga borders set along 58°N latitude and 22.6°E longitude (Fig. 1). CTD profiles were processed and analyzed with vertical resolution of 0.5 m (constant for all profiles) and only stations with depth over 20 m were used. Availability of CTD profiles differed widely between the years and months (Table 1).

Upper mixed layer (UML) depth was estimated using smoothed (2.5 m moving average) vertical profiles of density and the UML depth was defined at each vertical profile as the shallowest depth where the density difference between consecutive data points was equal or exceeded 0.05 $kg\,m^{-3}$. The latter value was derived empirically as a value which best reflects the start of pycnocline and, thus,

Table 1 The available CTD casts by year and month.

Year	May	June	July	August	Total
1993	15	–	–	11	26
1994	6	5	10	12	33
1995	19	17	15	15	66
1996	15	–	–	3	18
1997	–	3	–	–	3
1998	4	3	–	12	19
1999	2	–	9	–	11
2000	–	–	–	18	18
2001	29	–	8	20	57
2002	31	7	17	19	74
2003	31	9	10	30	80
2004	23	5	3	13	44
2005	11	9	–	12	32
2006	14	–	10	18	42
2007	29	–	17	23	69
2008	31	4	6	9	50
2009	28	–	3	24	55
2010	40	–	6	31	77
2011	20	–	6	15	41
2012	7	10	5	26	48
Total	355	72	125	311	863

the depth of UML. Smoothed vertical profiles of density were used to avoid possible fluctuations which might mislead the correct distinction of the UML by exceeding the selected density difference (0.05 kg m^{-3}) between consecutive data points. Deep layer (DL) was defined as a layer with depth >35 m and all estimated parameter characteristics of DL were obtained only from profiles deeper than 35 m. The salinity in the present study was expressed as absolute salinity [g kg^{-1}] and derived from CTD measured salinity values (on Practical Salinity Scale) using freely available software "Ocean Data View" (Schlitzer, 2010) and following TEOS-10 (Thermodynamic Equation Of Seawater — 2010) guidelines and Feistel et al. (2010).

River run-off data were calculated from monthly mean flow rates [m^3 s^{-1}] of four biggest rivers in Latvia discharging into the Gulf of Riga — Daugava, Gauja, Lielupe and Salaca (data provided by Latvian Environment, Geology and Meteorology Centre). The mouths of Daugava, Gauja and Lielupe are located in southern part, whereas, the mouth of Salaca in eastern part of the Gulf of Riga.

Available wind data were acquired from Sõrve (1995—2012), Ruhnu (2003—2012), Kihnu (1993—2011) and Pärnu (1993—2012) meteorological stations provided by Estonian Environment Agency. To characterize the atmospheric forcing conditions over the Gulf of Riga we analyzed the monthly-averaged Baltic Sea Index (BSI), which is the difference of normalized sea level pressures between Szczecin in Poland and Oslo in Norway (Lehmann et al., 2002; values provided by Andreas Lehmann).

Mean values of studied CTD parameters in May—August were estimated at the beginning as a simple arithmetic means of every month in each year. These values were further used to obtain the monthly mean values for the whole research period of 1993—2012 from which finally one mean value was derived for each parameter. For more detailed CTD parameter analyses we used only data from May and August and only those monthly mean values where available amount of CTD casts was equal or exceeded 5 casts in a month.

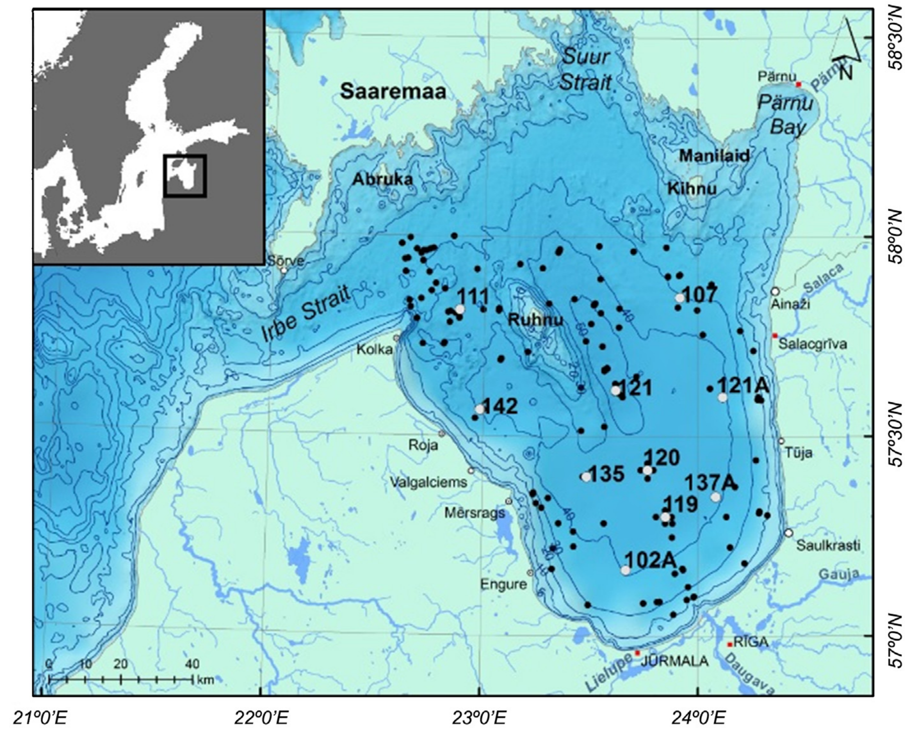

Figure 1 Bathymetric map of the Gulf of Riga with CTD cast locations indicated with black dots (all stations) and white dots (10 main stations with station labels).

Rossby radius was calculated numerically solving eigenvalue problem using Runge—Kutta scheme combined with trial-and-error approach. See Chelton et al. (1998) for more detailed information about definition and calculation of Rossby radius.

In order to analyze the dynamics of various parameters in different parts of the GoR ten "main" stations (102A, 135, 142, 111, 119, 120, 121, 137A, 121A, 107) were chosen determined by the data availability from these stations (Fig. 1).

3. Results

3.1. Upper mixed layer

From analyzed 863 CTD casts we were able to define UML in 533 of them. Regarding monthly distribution of defined UML, from 356 CTD casts in May we defined UML in 133 (37%) of them and from 75 (June), 125 (July) and 311 (August) casts we defined UML in 35 (48%), 98 (78%) and 267 (85%) of them, respectively.

The mean UML depth derived from all available CTD casts in the Gulf of Riga in the period of 1993—2012 (May—August) was 10.7 m. The shallowest mean UML depth in the research period was found in May (8.7 m), it was deeper in June (9.0 m) and July (11.5 m) but the deepest UML was detected in August (13.7 m) (Fig. 2).

The UML mean salinity and temperature in the whole period were 5.17 g kg^{-1} and 14.5°C, whereas density (expressed as sigma-t which is seawater density, where density value of 1000 kg m^{-3} has been subtracted) — 2.95 kg m^{-3}. Salinity and temperature increased from 4.90 g kg^{-1} and 8.0°C in May to 5.14 g kg^{-1} and 12.5°C in June, to 5.28 g kg^{-1} and 18.7°C in July and 5.38 g kg^{-1} and 18.6°C in August, respectively. Mean UML density in May, June, July and August was 3.59, 3.32, 2.39 and 2.48 kg m^{-3}, respectively (Fig. 2).

3.1.1. August

Greater amount of CTD casts in August allowed us to make more detailed inter-annual and long-term analysis of UML characteristics and suggest probable factors which may have impact on different UML parameters. The mean vertical structure of salinity in the GoR during 1993—2012 showed that salinity was about 5.3 g kg^{-1} at the surface and around 6.0 g kg^{-1} in the bottom layer, whereas, the mean vertical structure of temperature showed typical two-layer formation with thermocline situated approximately at 10—30 m depth (Fig. 3).

During the period of 1993—2012, the UML mean depth varied between different parts (10 main stations) of the GoR. Results showed that the UML mean depth was shallower in the western (W) part of the gulf ranging between 12.3 and 13.3 m (stations 111, 142, 135 and 102A), whereas, in the eastern (E) part the UML mean depth was deeper ranging between 14.6 and 15.4 m (stations 107, 121A and 137A). When looking at the section from the W to the E part of the GoR (stations 142-121-121A), an increase of the UML mean depth (start of the thermocline) can be observed (12.3, 14.2 and 14.6 m, respectively), thus, suggesting occurrence of differences between the two coastal areas in the gulf. The UML mean salinity also varied spatially during the research period. Results from 10 main stations revealed that on average the UML mean salinity was higher in the E part of the GoR (5.53, 5.42 and 5.37 g kg^{-1} at stations 107, 121A and 137A, respectively) and slightly lower values were observed in the W part of the gulf (5.36, 5.31, 5.31 and 5.29 g kg^{-1} at stations 111, 142, 135 and 102A, respectively). As expected, the UML mean salinity decreased towards the southern (S) part of the GoR where influence of river run-off is more pronounced than in the northern (N) part of the gulf.

The inter-annual variations of UML mean depth, temperature, salinity and density in August were noticeable but no clear tendency or trend could be detected in the period 1993—2012 (Fig. 4). Results from years 1993, 1994 and 2008 should be regarded with caution regarding the mean conditions in the gulf because of spatial distribution of stations in these years — in 1993 and 1994 the data only from the N and northwestern (NW) part and in 2008 only from the S part of the Gulf of Riga were available. This circumstance might explain rather big peaks in 1993 (UML mean depth) and 1994 (UML mean depth, temperature, density). Apart from that, the UML mean depth varied mainly between 10 and 20 m in the whole study period. Regarding the mean salinity, temperature and density, years 2003, 2006 and 2010 stand out from the whole period of inter-annual variability. Two salinity peaks were observed in 2003 (5.58 g kg^{-1})

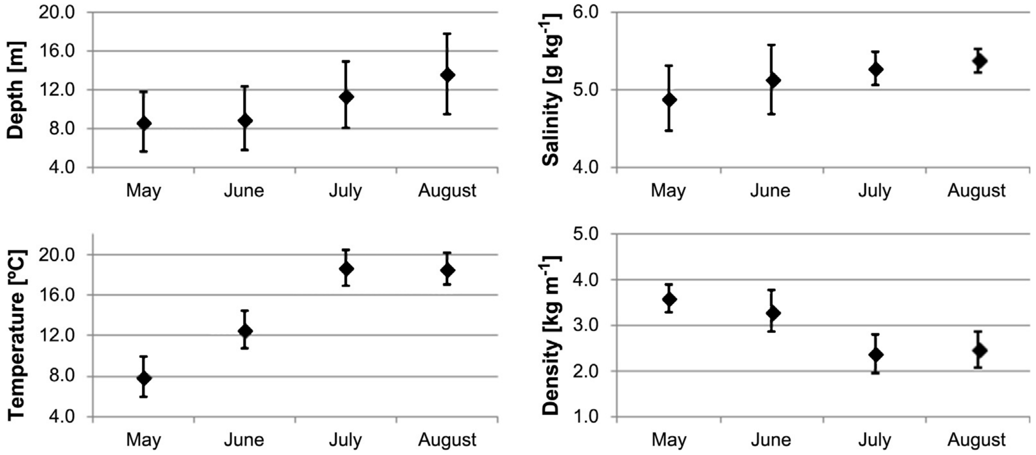

Figure 2 Mean characteristics of upper mixed layer between 1993 and 2012 (May—August) with standard deviations.

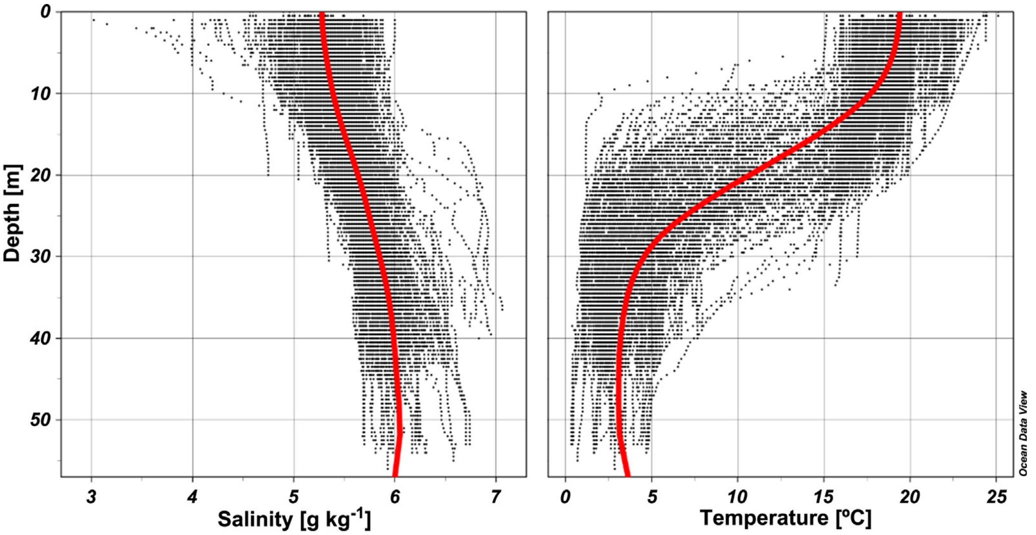

Figure 3 Scatter plot of vertical profiles of salinity and temperature in August, 1993—2012. The red line represents the mean vertical profile for the whole period. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

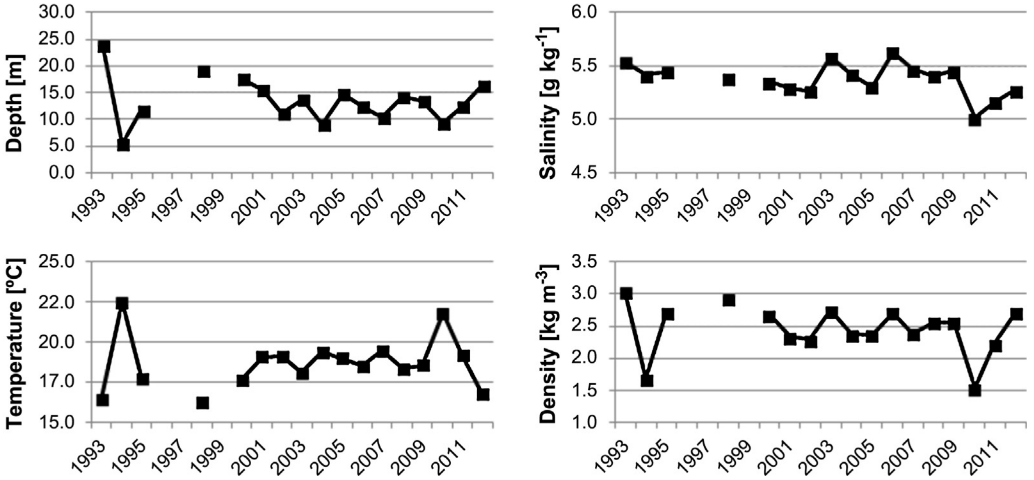

Figure 4 Inter-annual variability of mean characteristics of upper mixed layer in August, 1993—2012.

and 2006 (5.63 g kg^{-1}), respectively. However, year 2010 stood out as a year with the lowest salinity (5.01 g kg^{-1}) and density (1.53 kg m^{-3}) as well as with the second largest UML mean temperature (21.8°C) in the whole period. In addition, correlation was found between the UML mean temperature and UML mean depth ($r = -0.84$, $n = 17$, $p < 0.05$). Correlation remained significant (r values ranging from -0.58 to -0.8, $p < 0.05$) throughout the GoR when looking at specific parts (ten main stations).

A rather high correlation ($r = -0.66$, $n = 17$, $p < 0.05$) during 1993—2012 was found between the UML mean salinity (August) and mean river run-off in spring (March—May). Correlation increased even more ($r = -0.82$, $n = 14$, $p < 0.05$) when years 1993, 1994 and 2008 were taken out of calculations due to the insufficient data in regard of their spatial distribution. The above mentioned correlation remained high almost throughout the whole GoR when looking at specific parts/stations (Table 2) — the highest correlation was found in the S and southwestern (SW) part of the GoR at stations 119 ($r = -0.85$, $n = 13$, $p < 0.05$), 102A ($r = -0.80$, $n = 15$, $p < 0.05$) and 135 ($r = -0.81$, $n = 13$, $p < 0.05$), respectively. The lowest correlation was found in the E part of GoR at the stations 137A ($r = -0.66$, $n = 15$, $p < 0.05$), 121A ($r = -0.63$, $n = 14$, $p < 0.05$) and 107 ($r = -0.49$, $n = 14$, $p > 0.05$), respectively, with correlation decreasing further away from the S part of the GoR. A remarkably high correlation was still observed at the stations 121 ($r = -0.77$, $n = 17$, $p < 0.05$), 142 ($r = -0.77$, $n = 14$, $p < 0.05$) and 111 ($r = -0.76$, $n = 18$, $p < 0.05$), respectively, despite being relatively far away from the freshwater sources mostly located in the S part of the GoR.

The estimated UML parameters in August were correlated with the Baltic Sea Index and significant correlation was found between inter-annual changes of the UML mean depth and BSI in 1993—2012. The best correlation ($r = 0.71$, $n = 14$, $p < 0.05$) was found using mean BSI values from the period of June—August and excluding years 1993, 1994 and 2008 from the calculations as it was done before. Correlation was somewhat scattered when looking at specific parts/stations of the GoR (Table 2) — the highest correlation was found along

Table 2 Correlation between the upper mixed layer characteristics and various forcing factors in the Gulf of Riga during 1993—2012. Bold numbers indicate significant correlation ($p < 0.05$), *n* shows the number of years used in the analysis and "All stations" row shows the correlation between the average upper mixed layer characteristics over all stations and forcing factors.

Station	*n*	UML salinity (August) and river runoff (March—May)	UML depth (August) and Baltic Sea Index (June—August)	UML depth (August) and wind speed (August)
111	18	**−0.76**	**0.71**	**0.64**
142	14	**−0.77**	0.43	0.51
135	13	**−0.81**	**0.88**	0.37
102A	15	**−0.80**	**0.74**	0.51
119	13	**−0.85**	**0.56**	0.34
120	13	**−0.71**	0.18	0.13
121	17	**−0.77**	0.41	0.37
137A	15	**−0.66**	0.40	0.41
121A	14	**−0.63**	**0.66**	**0.56**
107	14	**−0.49**	**0.55**	0.01
All stations	14	**−0.63**	**0.71**	**0.59**

SW and W part of the GoR at stations 102A ($r = 0.74$, $n = 15$, $p < 0.05$), 135 ($r = 0.88$, $n = 13$, $p < 0.05$) and 111 ($r = 0.71$, $n = 18$, $p < 0.05$), respectively. Lower correlation was obtained at stations 107 ($r = 0.55$, $n = 14$, $p < 0.05$) and 121A ($r = 0.66$, $n = 14$, $p < 0.05$) in the E part of the GoR and at station 119 ($r = 0.56$, $n = 13$, $p < 0.05$) in the S part of the gulf but no significant correlation was found in the remaining stations — 137A, 120, 121 and 142. In addition, a probable link between the UML mean depth and wind speed (measured at the Sõrve meteorological station) was searched from the same period. Significant correlation was found ($r = 0.59$, $n = 14$, $p < 0.05$) between the UML mean depth in August and average wind speed (August). However, if we look at the specific parts/stations of the GoR then significant correlation was obtained only at two stations — 111 ($r = 0.64$, $n = 16$, $p < 0.05$) in the NW part and 121A ($r = 0.56$, $n = 14$, $p < 0.05$) in the E part of the GoR (Table 2).

3.2. Deep layer

Altogether, 558 CTD casts during the period of May—August, 1993—2012 with depth >35 m were available for deep layer analysis. The mean salinity, temperature and density derived for the whole period was 5.99 g kg^{-1}, 2.2°C and 4.68 kg m^{-3}, respectively.

Monthly mean salinity and density for the whole period showed negligible variations in the DL during May—August when the mean salinity and density fluctuated only by 0.06 g kg^{-1} and 0.04 kg m^{-3} between the months. Monthly mean DL temperature increased steadily from 1.4°C (May) to 1.9°C (June), 2.5°C (July) and 3.0°C (August), respectively (Fig. 5).

Greater amount of CTD casts in May and August allowed us to make more detailed inter-annual and long-term analysis about DL characteristics. Similarly to UML dynamics, inter-annual variations of mean temperature, salinity and density were evident but no clear tendency or trend could be detected in May or August during the period of 1993—2012 (Fig. 6). Results from years 1993 (stations only in NW part) in May and 1993, 1994 and 2008 in August should be regarded with caution regarding the mean conditions in the gulf because of spatial distribution of stations in these years (see Section 3.1.1). This might explain rather big salinity peak in 1994 (August). Apart from 1994, the peaks of DL mean salinity in August, 2006 and 2010 coincided well with similar peaks in May (seen also in density), whereas, the salinity peak

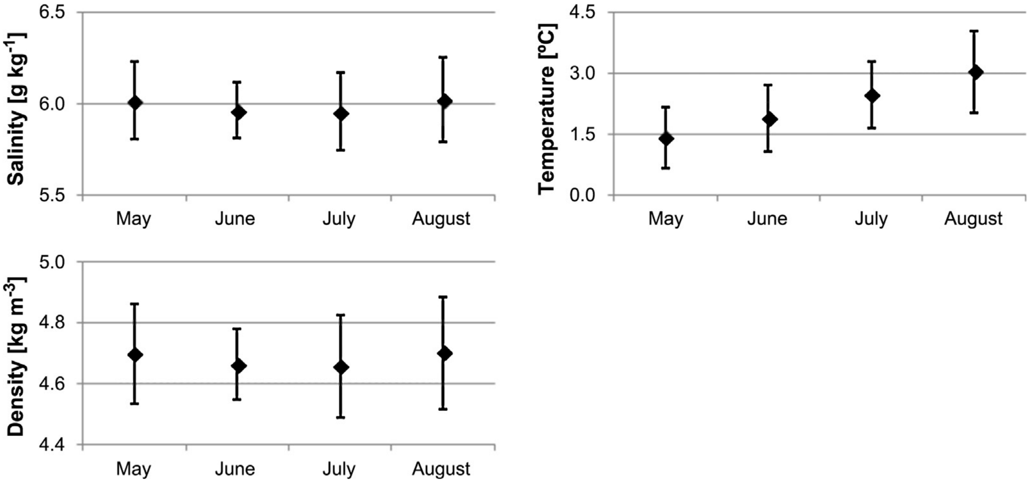

Figure 5 Mean characteristics of deep layer between 1993 and 2012 (May—August) with standard deviations.

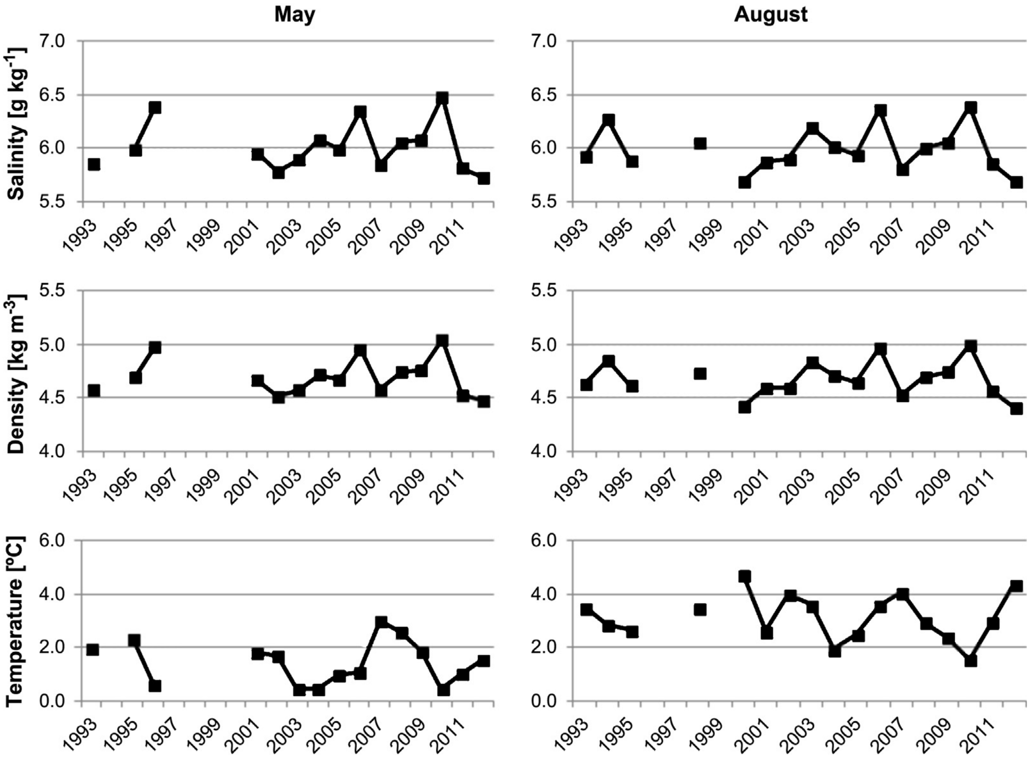

Figure 6 Inter-annual variability of mean characteristics of deep layer in May (left column) and August (right column), 1993—2012.

in 2003 was more pronounced in August (6.20 g kg^{-1}) than in May (5.89 g kg^{-1}) suggesting of more saline water inflow sometime between May and August. In May 1996 the second largest (6.40 g kg^{-1}) mean salinity was observed from the whole study period, whereas, in August only data from one station (121) was available with mean salinity of 6.46 g kg^{-1}.

As majority of water exchange between the GoR and Baltic Sea takes place through the Irbe Strait a possible connection was expected between DL characteristics in the Irbe Strait and DL in the GoR. High correlation ($r = 0.88$, $n = 12$, $p < 0.05$) during 1993—2012 was found in August between DL mean salinity in the Irbe Strait and DL mean salinity in the GoR. Similar correlation ($r = 0.84$, $n = 12$, $p < 0.05$) was observed regarding the DL mean density in both locations. Correlation between the previously mentioned DL mean salinity in the Irbe Strait and GoR was slightly different when looking at specific parts/stations of the GoR — the highest correlation was observed at the stations near the Irbe Strait and along the W coast of the gulf (stations 111, 142 and 135 with $r = 0.94$, 0.95 and 0.93, respectively, $p < 0.05$). Towards the S and southeastern (SE) part of the GoR correlation steadily decreased ($r = 0.83$, 0.76 and 0.71 at stations 102A, 119 and 137A, respectively, $p < 0.05$) whereas correlation was even lower in the central and E part of the gulf (stations 120, 121 and 121A with $r = 0.68$, 0.49 and 0.59, respectively, correlation not being significant at latter 2 stations). Analyzing all the data from May, the previously described connection between the DL mean parameters in the Irbe Strait and GoR was not significant regarding salinity and density. Nevertheless, when looking at specific stations significant correlation was still observed regarding salinity at 2 stations closest to the Irbe strait (111 and 142 with $r = 0.70$ and 0.67, respectively, $n = 10$, $p < 0.05$). Regarding density, the correlation was significant ($r = 0.72$, $n = 10$, $p < 0.05$) only at station 111.

The DL characteristic parameters in May and August were also correlated with the Baltic Sea Index. As expected, neither in May nor in August significant correlation was detected between BSI and any parameter characterizing DL when analyzing mean values from the whole GoR. Nevertheless, at some occasions in May the correlation was evident when using BSI averaged over May and March—May. In both cases significant negative correlation was found in S part of the gulf (station 119) between BSI (May and March—May) and salinity ($r = -0.55$ and -0.61, respectively) as well as density ($r = -0.58$ and -0.65, respectively, $n = 16$, $p < 0.05$). Similar negative correlation was observed at station 137A between averaged BSI (March—May) and salinity as well as density ($r = -0.57$ and -0.59, respectively). This negative correlation tendency between BSI and salinity and density was evident in other stations as well, although, it was not significant ($p > 0.05$).

3.3. Vertical stratification in August

Inter-annual and long-term variability of different parameters in May and August was analyzed in previous sections. To study the vertical stratification and its variability we used the month of August which had the best data coverage during the whole study period (Fig. 7). The average salinity, density (sigma-t) and temperature difference between the UML and DL during 1993—2012 was 0.62 g kg^{-1}, 2.22 kg m^{-3} and 15.5°C, respectively. Year 2010 remarkably stood out as a year where difference between the UML and DL characteristics was the greatest — difference in salinity, density and

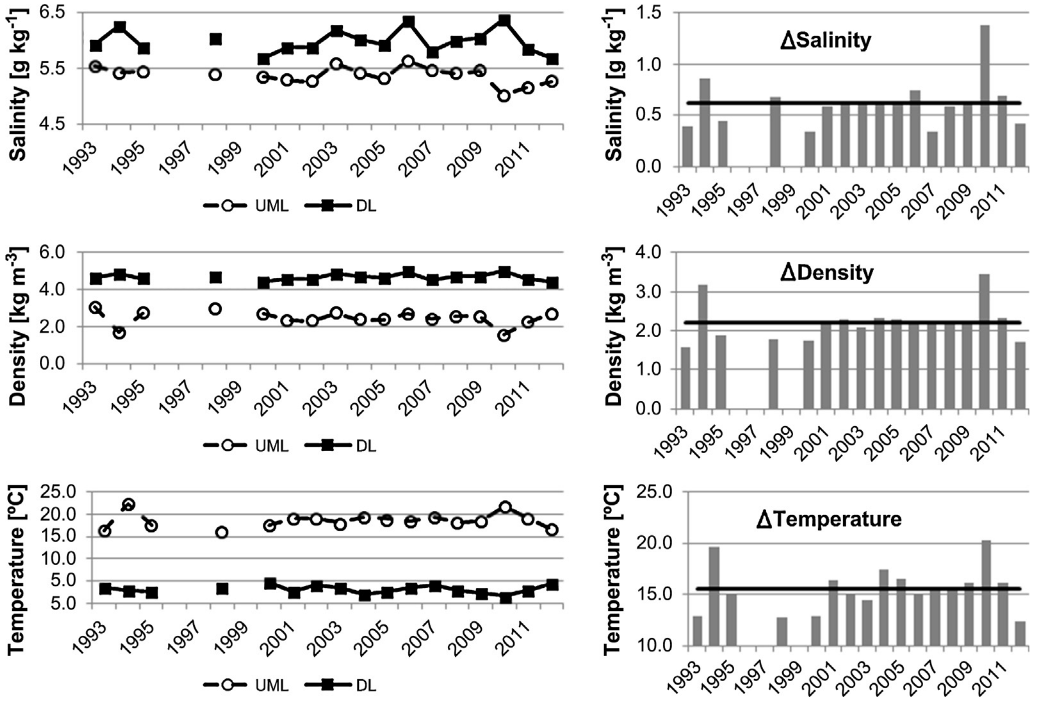

Figure 7 Mean salinity, density (sigma-t) and temperature in the upper mixed layer and deep layer in August 1993—2012 (left column) and their differences between the two layers (right column). Differences are given as deep layer minus upper mixed layer for salinity and density, and opposite for temperature; solid line represents the mean difference during 1993—2012.

temperature was 1.38 g kg^{-1}, 3.46 kg m^{-3} and 20.2°C, respectively. Salinity in the UML was the lowest (5.01 g kg^{-1}), whereas, in DL the highest (6.39 g kg^{-1}) from the whole period. Similar situation was observed regarding density — UML was characterized with the lowest (1.53 kg m^{-3}) and DL with the highest density (4.99 kg m^{-3}) in the whole period. The lowest DL mean temperature (1.6°C) was also observed in 2010 but the highest UML mean temperature (22.5°C) was observed in 1994 with the UML mean temperature in 2010 slightly lower at 21.8°C. In 1994 there was also observed rather high difference in mean salinity and density between UML and DL but this result should be treated with caution as in 1994 the data was available only from the N and NW part of the GoR.

Baltic Sea Index and river run-off was used to see whether any correlation could be found between the inter-annual changes of vertical stratification (expressed as salinity difference (ΔS) and density difference (ΔD) between the DL and UML and temperature difference (ΔT) between the UML and DL) and forcing factors. Results showed that there was no significant correlation between BSI mean values (values from August, June—August and July—August were tested) and any mentioned parameters (ΔS, ΔD and ΔT). On contrary, significant positive correlation was found between the river run-off in spring and corresponding ΔS, ΔD and ΔT with coefficient $r = 0.52$, 0.62 and 0.65, respectively ($n = 17$, $p < 0.05$).

3.4. Rossby radius

To estimate the characteristic values of Rossby radius in the GoR and, thus, corresponding scales of mesoscale features (eddies etc.) and to see whether there are some trends evident, we calculated Rossby radius in May and August using all available CTD profiles from ten main stations during 1993—2012.

The overall mean Rossby radius in May was roughly 2 times less than in August — 1.6 and 3.2 km, respectively. Inter-annual variability of mean Rossby radius was characteristic for both months but no conclusive trend could be observed in neither of them (Fig. 8). Although in August, in the beginning of 1990s the two lowest values of Rossby radius were observed (1993 and 1996), data only from 3 out of 10 stations were available and, thus, these results should be treated with caution. Similar situation was in August 1994 and in May 1993, 1994, 1998 and 1999. Nevertheless, August 2001, 2005 and 2010 stood out as years with the highest Rossby radius with values exceeding 3.5 km, whereas, in May, on the contrary, the lowest Rossby values in 2003 (0.9 km) and 2007 (1.2 km) were more distinguishable from the whole period.

During 1993—2012 the mean Rossby radius in May varied from 0.9—1.9 km, whereas, in August from 2.2—3.9 km. Although the mean Rossby radius is definitely higher in August than in May also some similarities and differences can be detected when looking at the spatial distribution of mean

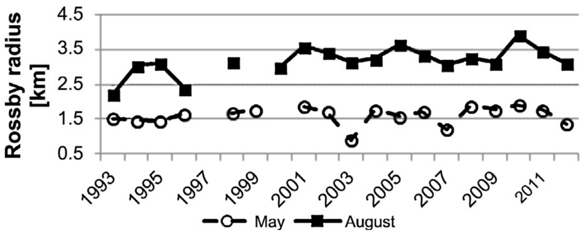

Figure 8 Mean Rossby radius in May and August during 1993—2012.

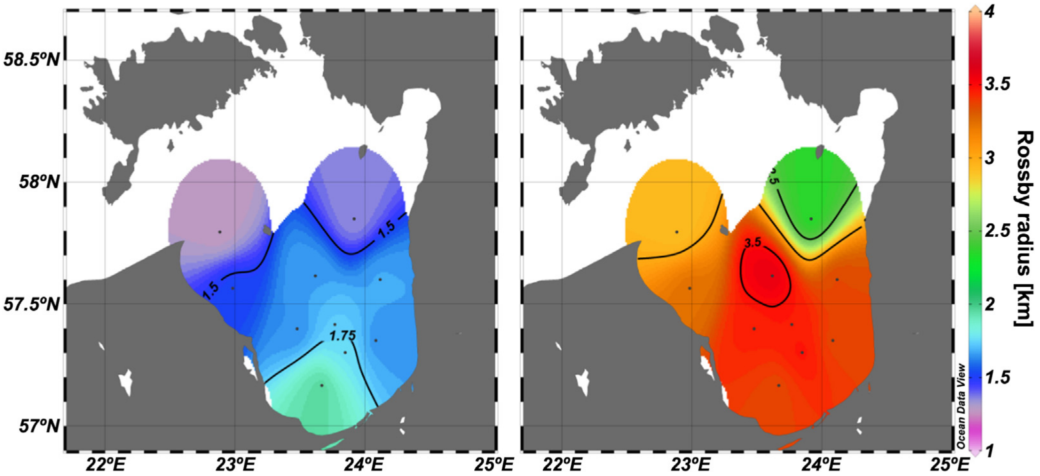

Figure 9 Mean Rossby radius in May (left) and August (right) at 10 main stations in the Gulf of Riga during 1993—2012.

Rossby radius in both months (Fig. 9). The lowest mean Rossby radius values can be observed at stations 111, 142 and 107 in both months — 1.3, 1.5 and 1.3 in May and 2.9, 3.2 and 2.3 km in August, respectively. In May the highest mean Rossby radius values can be seen in the S part of the GoR at stations 102A and 119 (2.0 and 1.8 km, respectively), whereas, in August the maximum value was found in the central part of the gulf at station 121 (3.6 km). In August the mean Rossby radius in the E part (3.4 km at stations 121A and 137A) and SW part (3.4 km at station 102A) was also somewhat lower (0.1 km on average) than at other stations situated more in the central (120 and 119) part of the GoR.

4. Discussion

Estimation of UML depth from CTD profiles, to our knowledge, has not been done before in the GoR with similar approach as in the present study. Although Stipa et al. (1999) and Tamminen and Seppälä (1999) concluded before that mixed layer depth increases from spring to late summer, both studies relied on the data from 4 surveys during 1993—1995 and referred to the data from one section when talking about mixed layer depth. Consequently, we needed to compare our findings with some other regions than GoR. Resembling research in the Gulf of Finland (GoF) by Liblik and Lips (2011) using CTD profiles and analyzing the vertical structure of the water column showed that the UML mean depth in the GoF (12.8 m) during 1987—2008 (June—August) is about 1.4 m deeper than in our findings about the GoR (using also June—August). The UML mean salinity in the GoR during 1993—2012 (May—August) was practically identical to those findings in the GoF (although they used Practical Salinity Scale as opposed to Absolute Salinity in our case), whereas, the UML mean temperature in June, July and August was about 0.7—1.8°C higher in the GoR, probably, due to the fact that the GoR is a shallower water basin accumulating and releasing the heat more rapidly. If the UML characteristics are quite similar in both water basins mentioned before, then substantial differences can be seen in the DL characteristics, mainly, due to the fact that both water basins are hydrographically diverse — GoR is a rather shallow, semi-enclosed sub-basin of the Baltic Sea as opposed to the GoF which is much more deeper and has an open access to the Baltic Sea. Thus, the DL mean salinity is about 2.5 g kg^{-1} higher in the GoF than in the GoR and mean temperature is lowest in the cold intermediate layer (as opposed to the DL) which, on the other hand, is not typical in the GoR where the lowest temperatures occur in the DL itself.

Analyzing the temperature and salinity values in the GoR at standard depths from 1973—1995 Raudsepp (2001) concluded that the mean salinity difference between surface and bottom is about 1 PSU which is substantially higher than what we obtained (0.62 g kg^{-1}) analyzing the month of August when the strongest stratification is expected. Comparing both studies we suggest that this difference between the surface and bottom layers is basically due to the increased bottom layer salinity during 1973 to 1995. In our study we had almost identical mean salinity (6.0 g kg^{-1}) in the DL (average from 35 m till bottom of the profile) from May to August in 1993—2012, whereas, in the results reported by Raudsepp (2001) at approximately 35 m depth salinity was around 6.1 PSU and increased more in the DL (about 6.5 PSU at the bottom). In addition, Raudsepp (2001) used Practical Salinity Scale for salinity, so each salinity value in his work is even higher if compared to Absolute Salinity, which is used in the present study. On the other hand, Stipa et al. (1999) reported of the density difference between the surface and deep waters in the middle of the summer being 1.5—2 kg m^{-3} using years 1993—1995 in their study. This is somewhat similar, although, a bit lower than we found out (2.2 kg m^{-3}) in our research during 1993—2012 (August).

Obtained mean Rossby radius values in May during 1993—2012 (0.9—1.9 km) were on average 2—2.5 times smaller than in the study where Rossby radius values from the model results were presented (Lips et al., 2016b). Such a discrepancy is caused by the different approaches used to calculate the Rossby radius. It has been showed before that in the whole Baltic Sea (Fennel et al., 1991) as well as in specific parts as the Gulf of Finland (Alenius et al., 2003) the Rossby radius has seasonal characteristics with minimum values during the autumn and winter and maximum values occurring in the summer mainly due to the strong stratification. Our results from the August correspond to these maximum Rossby radius values quite well exceeding the values in May almost two times. The stratification is strongest during the August in the GoR and the highest UML mean depth in August served as a good indicator for this in our research. In May, on the other hand, the GoR is partially stratified with mainly shallow UML but in approximately 2/3 of the CTD casts we were not able to detect distinctly developed UML in May. Strength of the stratification in the GoR is the main reason for Rossby radius differences in May and August. In August the Rossby radius was larger in the deeper parts (smaller in shallower parts) of the GoR which is in accordance to what has been found in the GoF (Alenius et al., 2003) and worldwide (Chelton et al., 1998). Nevertheless, in May the largest Rossby radius was observed in the S part of the gulf rather than in the central, deeper part. We suggest that this could be related to maximum river run-off occurring in spring and strongly influencing the surface layers starting from the S part of the gulf, thus, promoting stratification as well.

Seasonal changes in the UML mean depth in the GoR (May—August) showed similar characteristics as reported by Tamminen and Seppälä (1999) on the basis of data from 1993—1995 in the GoR and by Liblik and Lips (2011) using long-term data in the GoF, with depth increasing with each consecutive month. Estimated UML mean depth in the GoR in summer was shallower and mean temperature was warmer than that of the GoF, mainly because GoR is a shallower water basin than the GoF. The UML mean temperature also increased during May—August following the air temperature raise and, in general, this temperature dynamics corresponds well with previous studies (e.g. Berzinsh, 1995; Raudsepp, 2001) about seasonal variations of temperature in the GoR. Finally, the UML mean salinity during May—August increased steadily as well in the GoR and this dynamics is in accordance with previously mentioned study by Raudsepp (2001) where it was described that lower surface salinity in May is due to the maximum river run-off in the spring. A bit older studies by Berzinsh (1980, 1987) covering the periods 1963—1976 and 1971—1982, respectively, showed that mean salinity in June can be as low as in May and that the surface layer (0—10 m) mean salinity continued to slightly decrease also after May in June and the following increase started again from July. In these last two studies one can observe that the mean surface salinity is about 1.0 g kg^{-1} higher than we found in our results during 1993—2012. Seasonal changes in the DL characteristics are minor mainly due to the fact that there is no direct influence from the atmosphere.

Inter-annual variability dominated in our results during 1993—2012 and they did not reveal any unequivocal trends or tendencies in the UML or DL characteristics as opposed to previous studies where it was reported, for example, that salinity increased during 1960—1977 (e.g. Berzinsh, 1980, 1995) and decreased from the end of 1970s till the start of 1990s (Berzinsh, 1995; Raudsepp, 2001). Based on the data from 1976—2008 at four monitoring stations (standard depths) in the central and S part of the GoR, Jurgensone et al. (2011) reported about general increase of water temperature in the summer (June—September). Based on the satellite data during 1990—2004, Siegel et al. (2006) showed a positive trend in the yearly mean SST of the Baltic Sea with summer and autumn dominating this trend and positive summer trend being highest in the northern Baltic Sea. Similar analysis of remote sensing data from 1990—2008 (BACC, 2015) showed an increase of SST specifically in the GoR by about 1.0°C per decade. However, our results based on the CTD data in August did not show similar pattern with unequivocal temperature increase in the GoR during 1993—2012, although, apart from 1994, in general the UML mean temperature has increased from 1993—2010. Jurgensone et al. (2011) also noticed a salinity decrease before 1993 and a slight increase afterwards, whereas, there was no apparent trend in the stratification strength expressed as density difference between the surface (0—10 m) and subsurface layer. The latter corresponds well to our findings about the stratification strength (expressed as difference between the UML and DL) in August, whereas, we did not find any pronounced increase (or decrease) in the mean salinity in August during 1993—2012. Nevertheless, our results from August show that the mean salinity in last 3 years of the research period has been fairly lower compared with the values from the beginning of the 1990s.

Spatial distribution of the UML mean salinity from ten main stations in August showed higher salinity in the E coast than the W coast. In addition, the UML mean depth in August showed shallower UML depth in the W coast than in the central and E part of the gulf (UML mean depth in E part only slightly exceeded that in the central part). Therefore, it allows us to suggest that in the summer there is evident thermocline slope and corresponding sea level slope (opposite to the thermocline slope) between the two coasts and it is steeper in the W part of the GoR. Prevailing winds from WSW during the research period also indicate higher sea level in the E coast of the GoR. Thus, due to the average sea level gradient the general northward flow is dominating in the western part of the open gulf. This type of water flow is in accordance with the recent model results (Lips et al., 2016a) where it was reported that anticyclonic circulation exists in the GoR during summer forming a water tongue with lower salinity in the W part of the GoR.

High correlation found between the UML mean salinity (August) and the river run-off in spring during 1993—2012 confirmed the results of previous studies in the GoR (e.g. Berzinsh, 1995; Raudsepp, 2001) where it was shown that river run-off is the main factor for the salinity variations. A bit unexpected was the fact that high connection between these two factors was found not only in the S part of the gulf (majority of the freshwater discharges in this part) but, basically, throughout the gulf (10 main stations) and, especially, in the stations near the Irbe Strait. However, the mentioned model study by Lips et al. (2016a) also showed that during summer the anticyclonic (clockwise) circulation pattern dominates in the GoR, thus, transporting fresher surface waters from the south to north along the W coast of the gulf. Taking into account that our results showed also weaker correlation between the UML mean salinity and river run-off in spring on the E coast of the gulf, we feel that this general anticyclonic circulation (in the summer during stratified conditions) fits well with our findings and helps to explain them.

During the research period BSI (June—August) was found to be related ($r = 0.71$) to the UML mean depth (August) in the GoR. A positive BSI corresponds to an anomalous sea level pressure difference between Szczecin in Poland and Oslo in Norway (north-south distance of approximately 600 km) which means that the westerlies are prevailing over the Baltic Sea. If the BSI increases the winds from west are dominating and becoming stronger and, in general, stronger influence from the atmosphere should initiate more mixing in the UML and, thus, make it deeper. Obtained significant correlation between the average wind speed (August) and UML mean depth ($r = 0.59$) also adds up to this relation. Nevertheless, the results from 10 main stations showed that not always this correlation between the BSI and UML mean depth (as well as wind speed and UML mean depth) is significant and that it varies in different parts of the gulf which might be due to, for example, upwelling and downwelling events (e.g. Lehmann and Myrberg, 2008; Lehmann et al., 2012; Lips et al., 2009) or other factors which might have local influence on the water masses (mesoscale structures like eddies, filaments etc.). We suggest that, although atmospheric forcing undoubtedly plays an important role affecting the UML depth, it is only a part of explanation and more detailed research should be carried out in this direction to come up with more justified conclusions which are based on the data with better spatial and temporal resolution as we had.

At some occasions in May a connection (negative correlation) was found between the BSI (March—May) and DL mean salinity and density. We suggest that this is caused by the stronger winds and corresponding more intense vertical mixing. Although this negative correlation was not significant in all parts of the GoR (the overall correlation and correlation at some main stations was just over the chosen significance level of $p < 0.05$), it still was evident as a common tendency in all main stations. Taking into account that in May, on average, the GoR is not characterized by fully developed and permanent stratification, this might as well serve as a factor favouring water column mixing and transferring the impact of the atmosphere to the deep layers.

Inter-annual variations of the DL mean salinity in the GoR (August) are related to the DL mean salinity in the Irbe Strait (August). Best correlation was found in the W part of the gulf close to the Irbe Strait with correlation steadily decreasing towards the S part of the GoR, thus, suggesting that the inflow through the Irbe Strait continues anticlockwise along the W coast and penetrating deeper in the GoR. This corresponds well to what was previously reported regarding saline water inflow through Irbe Strait and further movement of the saline deep waters into the GoR (e.g. Berzinsh, 1995; Lilover et al., 1998).

For numerical modelling purposes in order to resolve mesoscale processes it is important to estimate the Rossby radius in the GoR. Our estimates of the Rossby radius in May and August showed that numerical models with horizontal grid spacing 1 km or less should be applied. Nevertheless, our temporal and spatial resolution of the CTD data did not allow us to determine Rossby radius in winter when the Rossby radius values are usually the lowest. Alenius et al. (2003) showed that the Rossby radius summer values are approximately 1.75 times the winter values in the centre of the Gulf of Finland. However, they also emphasized that the analysis is somewhat biased due to temporal distribution of the observations. Taking into account that the GoR is a shallower water basin than GoF and the water column is usually thoroughly mixed from the end of autumn till early spring, we speculate that Rossby radius in winter and early spring should be even lower than 1 km.

As previously discussed river run-off plays a major role affecting the salinity dynamics in the whole GoR. In addition to that, we also found a significant connection (positive correlation) between the mean river run-off in spring and stratification in August (expressed as difference between the temperature, salinity and density in the UML and DL) during 1993—2012. As river run-off increases it increases not only the salinity difference between the UML and DL but strengthens temperature and density difference as well. It means that river run-off in the GoR serves as instantaneous source of changes but it can also have further impact on the whole water column after some time. Maximum stratification found in 2010 serves as a good example for previously mentioned connection — in 2010 the second largest (after 1994) river run-off in spring was observed from the whole research period with following maximum strength of stratification observed later in August. Similar pattern can be observed in 1994 which was characterized by the largest river run-off in spring from the whole period. Although salinity difference between the UML and DL is considerably lower than in 2010 we suggest that this is due to the rather poor spatial distribution of the data (data available only from the N part of the gulf which is not affected by river run-off at the same level as the S part) and, judging by differences in temperature and density, the stratification in 1994 was at least as strong as in 2010.

Latest projections of the future climate change (BACC, 2015) continue to predict a significant water temperature increase in the Baltic Sea region similarly as it was stated before (BACC, 2008). Current study and results obtained using the CTD profiles from 20 years allows us to foresee the possible situation and changes in the GoR. We suggest that if the water temperature will continue to increase then the warming would generate a stronger stratification conditions in the GoR in summer. Furthermore, stronger stratification is likely to favour the oxygen depletion in the deeper parts of the gulf and following hypoxic or, at some cases, even anoxic conditions. Thus, the previously detected parts with low oxygen concentration or no oxygen at all (Hansson et al., 2009) in the GoR could expand in wider areas. Due to the projected strong decrease in sea-ice extent (BACC, 2015) the spring bloom could start earlier with possible shifts in dominating species characteristics as it was already suggested by Jurgensone et al. (2011). Moreover, with projected increase in the river run-off in winter (BACC, 2015), the nutrient amounts will also increase suggesting longer spring blooms with higher biomass.

Since 1977 there is an evident salinity decrease in the Baltic Proper and the GoR. Although it is not so pronounced since the beginning of the 1990s, most of the studies about future scenarios (see BACC, 2015) predict further salinity decrease. If so, then increase of freshwater species in the coastal areas is likely to occur.

While precipitation and evapotranspiration were projected to increase in the GoR region, the mean annual river run-off was projected to decrease. However, strong seasonal changes with shift of the maximum river run-off from spring to winter were also projected. We suggest that, due to the above mentioned factors, the salinity minimum usually observed (in the surface layers) starting from the spring in the S part of the gulf will also shift in accordance to changes in the river run-off seasonal dynamics. Earlier maximum river run-off together with water temperature increase could benefit for the faster development of permanent stratification in the GoR. Strong stratification could be observed already in May or even earlier as opposed to only partially stratified conditions (May) shown in the present study. Due to the stronger and earlier stratification in spring which hinders the vertical mixing, riverine water discharging mainly into the S part of the gulf could be transported for longer distances away from the coast. Such freshwater dynamics would have an impact on surrounding water masses by, for example, bringing more nutrient-rich water in the surface layers and increasing total suspended matter content in the areas where it was previously not observed or the effect was minor.

In conclusion, we showed that relatively large interannual variations dominated in the temporal variability of different UML and DL parameters and no clear long-term trend could be detected in the GoR during 1993—2012. The UML mean depth was found to be related to the Baltic Sea Index. River run-off proved to be a major driving force for the salinity dynamics and a substantial contributor to enhancing the strength of the stratification in summer. The analysis of inter-annual variations in density difference between the UML and DL revealed that the strongest stratification was observed in the years with the highest UML mean temperature and highest river run-off during spring. We suggest that the predicted water temperature increase and seasonal changes in river run-off will result in a stronger stratification in the GoR.

Acknowledgements

This work was supported by institutional research funding IUT19-6 of the Estonian Ministry of Education and Research, the DoRa programme activity 4 “Doctoral studies of talented international students in Estonian universities”. We thank our colleagues who have participated in the analyzed CTD data collection during 1993—2012. We are grateful to Viesturs Berzinsh and Andreas Lehmann who provided CTD data and BSI values, respectively.

References

Alenius, P., Nekrasov, A., Myrberg, K., 2003. Variability of the baroclinic Rossby radius in the Gulf of Finland. Cont. Shelf Res. 23 (6), 563—573.

BACC, 2008. Assessment of Climate Change for the Baltic Sea Basin. Springer Verlag, Berlin, 35—221.

BACC, 2015. Second Assessment of Climate Change for the Baltic Sea Basin. SpringerOpen, Geesthacht, 69—263.

Berzinsh, V., 1980. Interannual and seasonal changes of water salinity in the Gulf of Riga. Rybokhozyaistvennye issledovaniya (BaltNIIRKH), vol. 15, Avots, Riga, 3—12, (in Russian).

Berzinsh, V., 1987. Hydrological dividing of the open part of the Gulf of Riga. In: Andrusaitis, G.P., Laganovska, R.Y., Apine, S.O. (Eds.), Hydrochemical and Hydrobiological Characteristics and Dividing of the Coastal Part of the Baltic Sea, Gulf of Riga and Gulf of Finland, Zinatne, Riga, 7—20, (in Russian).

Berzinsh, V., 1995. Hydrology. In: Ojaveer, O. (Ed.), Ecosystem of the Gulf of Riga Between 1920 and 1990. Estonian Acad. Publ., Tallinn, 7—32.

Chelton, D.B., DeSzoeke, R.A., Schlax, M.G., Naggar, K.E., Siwertz, N., 1998. Geographical variability of the first baroclinic Rossby radius of deformation. J. Phys. Oceanogr. 28 (3), 433—460.

Feistel, R., Weinreben, S., Wolf, H., Seitz, S., Spitzer, P., Adel, B., Nausch, G., Schneider, B., Wright, D.G., 2010. Density and absolute salinity of the Baltic Sea 2006—2009. Ocean Sci. 6 (1), 3—24.

Fennel, W., Seifert, T., Kayser, B., 1991. Rossby radii and phase speeds in the Baltic Sea. Cont. Shelf Res. 11 (1), 23—36.

Hansson, M., Axe, P., Andersson, L., 2009. Extent of anoxia and hypoxia in the Baltic Sea, 1960—2009. SMHI Report Mo 2009-214, http://www.smhi.se/polopoly_fs/1.10354!Oxygen_timeseries_1960_2009.pdf.

Jurgensone, I., Carstensen, J., Ikauniece, A., Kalveka, B., 2011. Long-term changes and controlling factors of phytoplankton community in the Gulf of Riga (Baltic Sea). Estuaries Coasts 34 (6), 1205—1219.

Kotta, J., Kotta, I., Simm, M., Põllupüü, M., 2009. Separate and interactive effects of eutrophication and climate variables on the ecosystem elements of the Gulf of Riga. Estuar. Coast. Shelf Sci. 84 (4), 509—518.

Kõuts, T., Håkansson, B. (Eds.), 1995. Observations of Water Exchange, Currents, Sea Levels and Nutrients in the Gulf of Riga. SMHI RO Series No. 23, Norrköping. 141 pp.

Kronsell, J., Andersson, P., 2014. Total and regional runoff to the Baltic Sea. HELCOM Baltic Sea Environment Fact Sheets, http://www.helcom.fi/baltic-sea-trends/environment-fact-sheets/ (accessed: 11 November 2015).

Lehmann, A., Krauss, W., Hinrichsen, H.-H., 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. Tellus A 54 (3), 299—316.

Lehmann, A., Myrberg, K., 2008. Upwelling in the Baltic Sea — a review. J. Marine Syst. 74 (Suppl.), S3—S12.

Lehmann, A., Myrberg, K., Höflich, K., 2012. A statistical approach to coastal upwelling in the Baltic Sea based on the analyses of satellite data for 1990—2009. Oceanologia 54 (3), 369—393, http://dx.doi.org/10.5697/oc.54-3.369.

Leppäranta, M., Myrberg, K., 2009. Physical Oceanography of the Baltic Sea. Praxis Publ. Ltd., Chichester, 46 pp.

Liblik, T., Lips, U., 2011. Characteristics and variability of the vertical thermohaline structure in the Gulf of Finland in summer. Boreal Environ. Res. 16 (Suppl. A), 73—83.

Lilover, M.J., Lips, U., Laanearu, J., Liljebladh, B., 1998. Flow regime in the Irbe strait. Aquat. Sci. 60 (3), 253—265.

Lips, I., Lips, U., Liblik, T., 2009. Consequences of coastal upwelling events on physical and chemical patterns in the central Gulf of Finland (Baltic Sea). Cont. Shelf Res. 29 (15), 1836—1847.

Lips, U., Zhurbas, V., Skudra, M., Väli, G., 2016a. A numerical study of circulation in the Gulf of Riga, Baltic Sea. Part I: Whole-basin gyres and mean currents. Cont. Shelf Res. 112, 1—13.

Lips, U., Zhurbas, V., Skudra, M., Väli, G., 2016b. A numerical study of circulation in the Gulf of Riga, Baltic Sea. Part II: Mesoscale features and freshwater transport pathways. Cont. Shelf Res. 115 (1), 44—52.

Petrov, V.S., 1979. Water balance and water exchange between the Gulf of Riga and the Baltic Proper. In: Sbornik rabot rizhskoj gidrometeorologicheskoj observatorii, 18, Riga. 20—40, (in Russian).

Raudsepp, U., 2001. Interannual and seasonal temperature and salinity variations in the Gulf of Riga and corresponding saline water inflow from the Baltic Proper. Hydrol. Res. 32 (2), 135—160.

Schlitzer, R., 2010. Ocean Data View, http://odv.awi.de.

Siegel, H., Gerth, M., Tschersich, G., 2006. Sea surface temperature development of the Baltic Sea in the period 1990—2004. Oceanologia 48 (S), 119—131.

Stiebrins, O., Väling, P., 1996. Bottom Sediments of the Gulf of Riga. Geological Survey of Latvia, Riga, 4 pp.

Stipa, T., Tamminen, T., Seppälä, J., 1999. On the creation and maintenance of stratification in the Gulf of Riga. J. Marine Syst. 23 (1—3), 27—49.

Tamminen, T., Seppälä, J., 1999. Nutrient pools, transformations, ratios, and limitation in the Gulf of Riga, the Baltic Sea, during four successional stages. J. Marine Syst. 23 (1—3), 83—106.