Original Russian Text © The Authors, 2022,
published in MORSKOY GIDROFIZICHESKIY ZHURNAL, Vol. 38, Iss. 6 (2022)

Stationary and Non-Stationary Description of the Seasonal Sea Level Oscillations in the Baltic Sea Based on the Tide Gauge Data

E. A. Zakharchuk [1, 2], V. N. Sukhachev [1, 2] ✉, N. A. Tikhonova [1, 2],
E. N. Litina [1, 2]

[1] *St Petersburg University, Saint Petersburg, Russian Federation*
[2] *N. N. Zubov State Oceanographic Institute, Moscow, Russian Federation*
✉ *syhachev@mail.ru*

Abstract
Purpose. The main purpose of the paper is to estimate in a stationary approximation the magnitudes of the amplitude-phase characteristics of the sea level seasonal fluctuations in the Baltic Sea in 1971–2020, and to study the features and possible reasons for their non-stationarity.
Methods and Results. The description of seasonal fluctuations is substantiated by a sum of 4 harmonics: the annual (*Sa*), semiannual (*Ssa*), terannual (*Sta*) and quarterannual (*Sqa*) ones. The average values of the Baltic Sea level seasonal fluctuations, as well as their interannual variability are estimated using a harmonic analysis of the average daily values of the tide gauge data. The results indicate that the amplitudes of the harmonics *Sa*, *Ssa*, *Sta* and *Sqa* are reliably distinguished for all the coastal points under study. The features of the phase spatial distribution testify to a statistically reliable propagation of the sea level disturbances with a one-year period from the southwest to the north and to the northeast. For the other components of the sea level seasonal fluctuations (*Ssa*, *Sta* and *Sqa*), the spatial phase changes are very small and comparable to the standard errors of their calculation. The amplitude modulation with a period of about 20 years for the *Ssa* harmonic and approximately 2–10 years for the *Ssa*, *Sta* and *Sq*a ones is well pronounced in the interannual changes in the Baltic Sea level seasonal fluctuations. A significant negative trend for all the stations is observed in the time series of the *Sa* harmonic amplitudes in 1971–2020. In order to clarify the reasons of the revealed features of the *Sa* harmonic interannual changes, a non-stationary harmonic analysis of the atmospheric pressure series, wind and the sea level steric fluctuations is done in the study.
Conclusions. It is shown that the changes in the annual sea level fluctuations observed in 1971–2020 are mostly influenced by the anomalies of annual wind fluctuations, and to a lesser extent, by those of the atmospheric pressure.

Keywords: sea level, seasonal fluctuations, harmonic analysis, interannual variability, trends, wind, atmospheric pressure, steric fluctuations

Acknowledgements: The study was carried out with financial support of the Russian Science Foundation grant No. 22-27-00209.

For citation: Zakharchuk, E.A., Sukhachev, V.N., Tikhonova, N.A. and Litina, E.N., 2022. Stationary and Non-Stationary Description of the Seasonal Sea Level Oscillations in the Baltic Sea Based on the Tide Gauge Data. *Physical Oceanography*. 29(6), pp. 636-658. doi:10.22449/1573-160X-2022-6- 636-658

DOI: 10.22449/1573-160X-2022-6-636-658

Introduction

Seasonal course of the Baltic Sea level is manifested in its decrease in winter to a minimum value in April–May and an increase in summer–autumn to a maximum in November–January [1–3]. This seasonal rhythm in the Baltic level surface position is associated with seasonal changes in wind, atmospheric pressure, currents, seawater density and water balance components (precipitation, evaporation, continental runoff and water exchange with the North Sea) [4]. The quasi-stationary component of seasonal fluctuations in the Baltic Sea level is well expressed and is reliably identified using harmonic and spectral analyzes of long-term series of mean monthly sea level values [1, 5, 6].

Seasonal sea level fluctuations play an important role in the hydrological regime of the Baltic Sea. They make a noticeable impact on the coasts and coastal infrastructure of the Baltic [7, 8] and are indicators of its water exchange with the North Sea [9–11]. Seasonal level fluctuations are also indicators of ongoing changes in meteorological processes [4] and observed climate warming [12]. Our studies show that the contribution of seasonal fluctuations of the Baltic Sea to dangerous level rises in the east of the Gulf of Finland in some years can reach 26% [13]. The numerical experiments on a three-dimensional baroclinic model indicate that significant amplitude natural fluctuations of the Baltic Sea are excited not only in the range of periods from several hours to 2 days, as previously thought [14], but also in the seasonal variability range [15].

The studies of the spatial variability of seasonal fluctuations in the Baltic Sea level were carried out based on the results of a harmonic analysis of long-term series of mean monthly level values obtained from the tide gauge [5, 6]. The results showed that the amplitude of fluctuations varies with an annual period from 4–6 cm in the Danish Straits to almost 13 cm in the Gulf of Finland and in the north of the Gulf of Bothnia. The amplitudes of the semi-annual component of seasonal fluctuations turned out to be several times smaller and varied from 1–2 cm in the Kattegat and Danish Straits up to 5 cm in the Gulf of Finland and in the shallow part of the Baltic in the area of the Aland Islands, where they reached 5.7 cm, as well as near the eastern coast of Sweden in the Sea of Bothnia (5.1–5.6 cm) and in the central part of the Gulf of Finland (5.2 cm) [5, 6]. The value of mean fluctuations’ phase increased by 30º when moving from the Danish Straits through the open part of the Baltic Sea to the top of the Gulf of Bothnia. The phase of the semi-annual harmonic in the Baltic Sea varied from 20º in the Kattegat to 50º in the north of the Gulf of Bothnia in the very south of the Sea of Bothnia [6].

The authors of [16] using a moving Fourier analysis of a series of mean monthly sea level values at Stockholm station for 1825–1984 estimated the interannual variability of the amplitudes of the annual and semi-annual components of seasonal fluctuations. Their results showed a significant positive trend in changes in the annual sea level component. They suggested that this trend may be associated with secular changes in oceanographic conditions in the northeastern part of the North Atlantic. The manifestations of these changes are the movements of the oceanic polar front [16]. In his other work, studying secular changes in seasonal sea level fluctuations at Stockholm station, the author [17] concludes that they are associated with interannual changes in seasonal wind fluctuations in the transition zone between the North and Baltic Seas.

Later studies also revealed a positive trend in the amplitudes of the annual component of seasonal level fluctuations in the Baltic Sea, which the authors associate with the North Atlantic Oscillation on a decadal time scale and with the general trend of climate warming [18], as well as with secular changes in atmospheric precipitation in the Baltic Sea region [19].

The authors of [20] studied interannual changes in the annual component of seasonal fluctuations in the Baltic Sea level over 1900–2012 according to its monthly averages at 9 coastal stations using discrete wavelet analysis. They did not reveal a positive linear trend in the change in the amplitude of the annual component of seasonal sea level fluctuations, which was found by other authors [16, 18, 19], but they discovered alternating periods of high and low amplitudes in changes in the annual cycle of seasonal sea level fluctuations.

In [21], the seasonal level variability at one point in the open Baltic was estimated using satellite altimetry data by averaging the level values for every day and every month of the year for 18-year period. The results obtained were compared with similar estimates made on the basis of tide gauge data at several coastal stations. The relationship between monthly mean altimetry level values and river flow data for 75 largest rivers flowing into the Baltic Sea was also considered in the present paper. The comparison did not show any correlation between the processes analyzed [21].

The authors of [2] used the method of cyclostationary empirical orthogonal functions to study the regularities of the spatial structure and temporal changes in the annual level cycle in the Baltic Sea based on monthly average satellite altimetry data, tide gauge data of the sea level and data of the regional model reanalysis of physical processes in the Baltic Sea for 1993–2014. They found that the maxima of the annual level course were observed from December to February, and the minima in April – May. To study the causes of interannual changes in estimates of the annual variation of the Baltic Sea level, the authors carried out a cross-correlation analysis between the main components of the annual sea level variation, calculated from satellite altimetry data and the main components of various meteorological parameters (zonal wind, values of the North Atlantic Oscillation index, atmospheric pressure and air temperature). The results showed high estimates of correlation coefficients in all cases, reaching values of 0.60–0.80.

The analysis of the listed works shows that the estimates of the characteristics of seasonal fluctuations in the Baltic Sea level were carried out in the vast majority of cases based on long-term series of mean monthly level values obtained tide gauge data at a network of coastal hydrometeorological stations and satellite altimetry. However, the author of [22] showed that, due to the non-equidistance of monthly average data, estimates of the amplitudes and phases of the components of seasonal level fluctuations have errors. To improve the accuracy of estimates, they should be calculated from series of mean daily or hourly level values. The studies of interannual changes in seasonal fluctuations based on monthly average data, carried out using harmonic analysis by calculating their amplitudes and phases for each year [6], show a decrease in level series to 12 values per year, which affects the accuracy of their estimates. The studies of seasonal fluctuations obtained on the basis of long-term averaging of mean daily level values for each day of the year [21] cannot be considered reliable, since they contain contributions from quasi-stationary fluctuations from the low-frequency range of the synoptic scale of variability, which are revealed even with a visual analysis of mean daily level series smoothed in this way [21]. The causes of interannual changes in the characteristics of seasonal fluctuations in the Baltic Sea level remain poorly understood.

The present paper is aimed at estimating, using a harmonic analysis of the series of mean daily values of tide gauge of the sea level, the amplitude-phase characteristics of the four components of seasonal fluctuations in the Baltic Sea level (*Sa*, *Ssa*, *Sta* and *Sqa*) for 1971–2020 in the stationary approximation and taking into account the non-stationarity of the process, as well as to study the possible causes of their interannual changes.

Data and methods

To study seasonal fluctuations in the Baltic Sea level, the mean daily and monthly data of tide gauge data at 29 coastal stations of the Baltic Sea (Fig. 1) of various duration, obtained from the resources of E.U. Copernicus Marine Service Information (Available at: http://marine.copernicus.eu) and PSMSL (Available at: http://psmsl.org) [23] were used; and for Pionerskij, Kronstadt, Gornyy Institut and Vyborg stations, the data from the North-Western Department of Roshydromet were used. Table 1 gives this data array description. For 24 stations, the duration of the mean daily series was 50 years (1971–2020), for Pionerskij station – 43 years (1977–2020). The series of mean daily level values at Stockholm station for 1889–2020 had the longest duration. For comparison, the data of mean monthly sea level values at 6 stations for different periods of time were also used (Table 1).

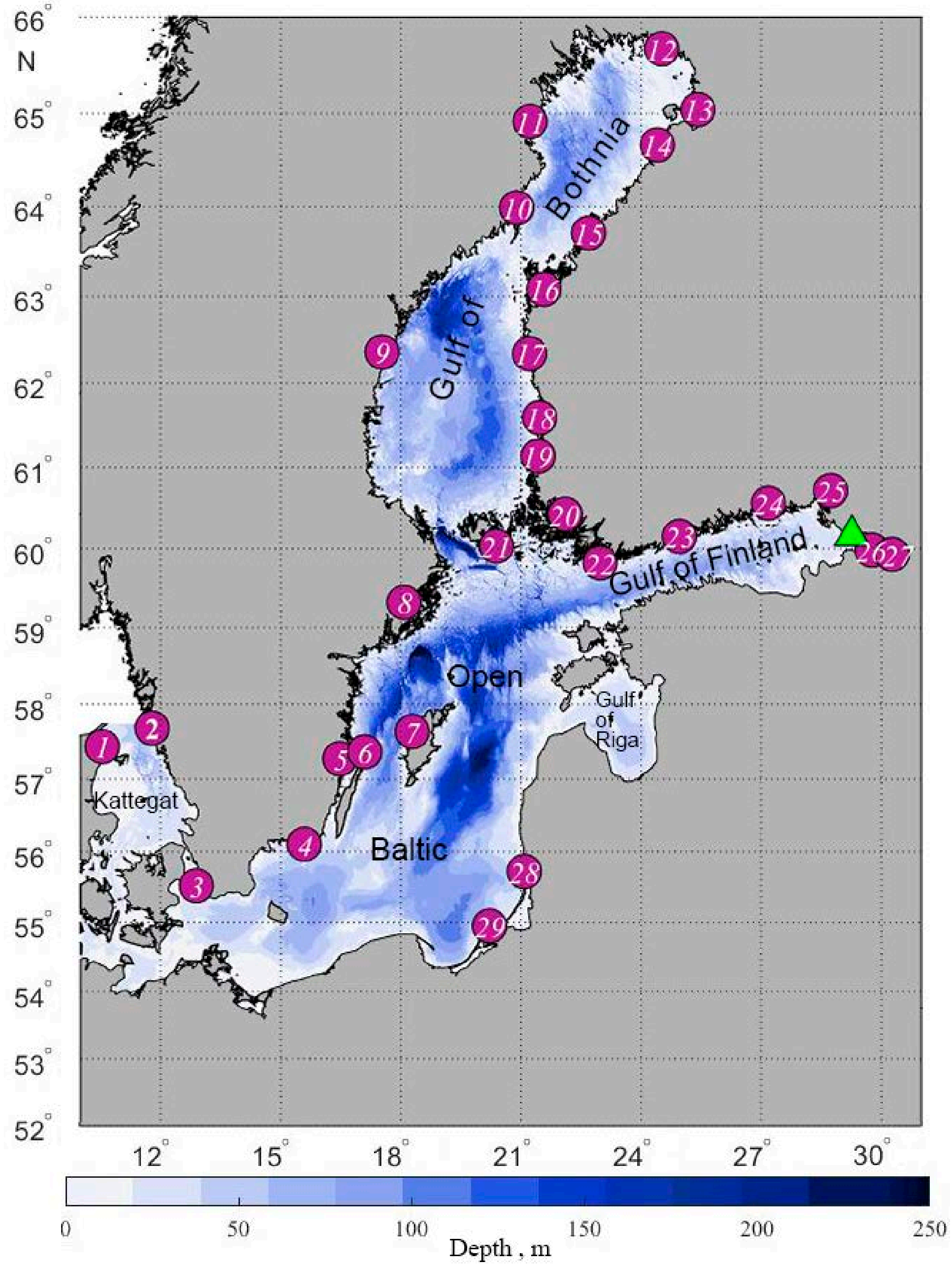
For the vast majority of sea level data series, the number of gaps was less than 1%, and only in six cases their number changed in the range of 2.1–8.1% (Table 1).

The amplitudes (*A*) and phases (*G*) of the seasonal level fluctuations in the stationary approximation were calculated using a harmonic analysis carried out by the least squares' method, taking into account the recommendations presented in [24]. Four harmonics were estimated: annual (*Sa*) – 365.2 days, semiannual (*Ssa*) – 182.6 days, terannual (*Sta*) – 121.8 days and quarterannual (*Sqa*) – 91.3 days:

$$A(t) = A_{sa}\cos(\omega_{sa}t - G_{sa}) + A_{ssa}\cos(\omega_{ssa}t - G_{ssa}) + \\ + A_{sta}\cos(\omega_{sta}t - G_{sta}) + A_{sqa}\cos\left(\omega_{sqa}t - G_{sqa}\right), \quad (1)$$

where A_{sa}, A_{ssa}, A_{sta} and A_{sqa} are the amplitudes of the indicated harmonics, respectively; G_{sa}, G_{ssa}, G_{sta} and G_{sqa} are the phases of these harmonics; ω_{sa}, ω_{ssa}, ω_{sta} and ω_{sqa} are the frequencies of the harmonics; t is the time. Based on the estimated amplitudes and phases, the series of all four harmonics of seasonal sea level fluctuations were built.

The choice of four harmonics to describe the seasonal variation of the sea level, and not two, as was done in other works [5, 16, 25], was dictated by a comparison of the seasonal level variation observed from tide gauge data with its description of two (*Sa, Ssa*) and four (*Sa, Ssa, Sta* and *Sqa*) harmonics, which is shown in Fig. 2.

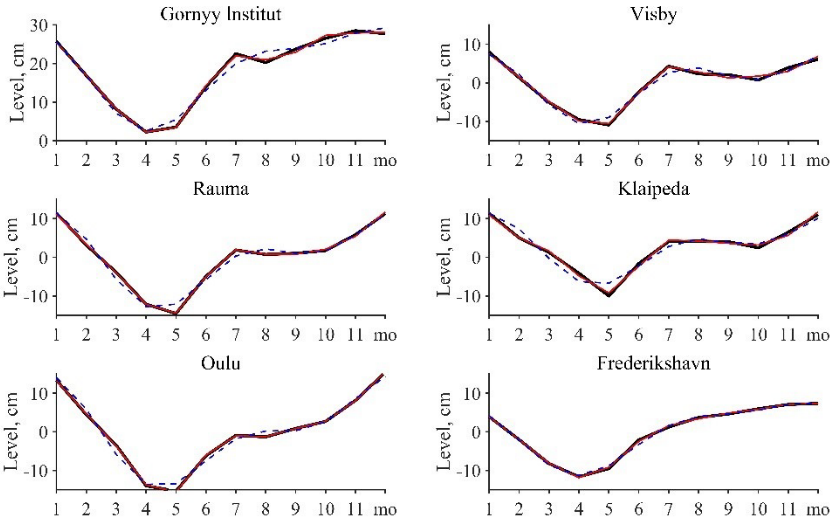


F i g. 1. Bathymetry of the Baltic Sea (shades of blue color). Circles with numbers denote the location of the tide gauge stations: 1 – Frederikshavn; 2 – Gothenburg; 3 – Klagshamn; 4 – Kangsholmfort; 5 – Oskarshamn; 6 – Olands; 7 – Visby; 8 – Stockholm; 9 – Spikarna; 10 – Ratan; 11 – Furuogrund; 12 – Kemi; 13 – Oulu; 14 – Raahe; 15 – Pietersari; 16 – Vasa; 17 – Kaskinen; 18 – Pori; 19 – Rauma; 20 – Turku; 21 – Degerbi; 22 – Hanko; 23 – Helsinki; 24 – Hamina; 25 – Vyborg; 26 – Kronstadt; 27 – Gornyy Institut; 28 – Klaipeda; 29 – Pionerskij. Green triangle indicates the hydrometeorological station Ozerki, yellow square – the BY-15 station

Table 1

Sea level tide gauge data at the coastal stations in the Baltic Sea

No	Station name	Coordinates		Measurement interval	Measurement period		Number of measurements	Gaps, %
		N	E		beginning	end		
1	Frederikshavn	57.4	10.5	1 month	1889	2017	1541	0.0
2	Gothenburg	57.7	11.8	1 day	1971	2020	18263	0.0
3	Klagshamn	55.5	12.9	1 day	1971	2020	18263	0.0
4	Kangsholmfort	56.1	15.6	day	1971	2020	18263	0.0
5	Oskarshamn	57.3	16.5	1 day	1971	2020	18263	0.4
6	Olands	57.4	17.1	1 day	1971	2020	18263	4.0
7	Visby	57.6	18.3	1 day	1971	2020	18263	0.2
7	Visby	57.6	18.3	1 day	1916	2020	1260	0.0
8	Stockholm	59.3	18.1	1 day	1889	2020	18263	0.0
9	Spikarna	62.4	17.5	1 day	1971	2020	18263	0.1
10	Ratan	64.0	20.9	1 day	1971	2020	18263	0.0
11	Furuogrund	64.9	21.2	1 day	1971	2020	18263	0.2
12	Kemi	65.7	24.5	1 day	1971	2020	18263	2.4
13	Oulu	65.0	25.4	1 day	1971	2020	18263	0.1
13	Oulu	65.0	25.4	1 month	1889	2019	1572	4.3
14	Raahe	64.7	24.4	1 day	1971	2020	18263	0.1
15	Pietersari	63.7	22.7	1 day	1971	2020	18263	0.1
16	Vasa	63.1	21.6	1 day	1971	2020	18263	0.1
17	Kaskinen	62.3	21.2	1 day	1971	2020	18263	0.5
18	Pori	61.6	21.5	1 day	1971	2020	18263	2.1
19	Rauma	61.1	21.4	1 day	1971	2020	18263	0.1
19	Rauma	61.1	21.4	1 month	1933	2019	1044	0.6
20	Turku	60.4	22.1	1 day	1971	2020	18263	0.1
21	Degerbi	60.0	20.4	1 day	1971	2020	18263	0.1
22	Hanko	59.8	23.0	1 day	1971	2020	18263	0.1
23	Helsinki	60.2	25.0	1 day	1971	2020	18263	0.1
24	Hamina	60.6	27.2	1 day	1971	2020	18263	0.1
25	Vyborg	60.7	28.7	1 day	1971	2020	18263	0.5
26	Kronstadt	60.0	29.8	1 day	1971	2020	18263	0.3
27	Gornyy Institut	59.9	30.3	1 day	1971	2004	336	0.0
28	Klaipeda	55.7	21.1	1 month	1898	2018	1452	8.1
29	Pionerskij	55.0	20.2	1 day	1977	2020	16071	4.3



F i g. 2. Average seasonal changes in the sea level at different stations of the Baltic Sea (black curve) resulted from the tide gauge data, and its values pre-calculated by the harmonic analysis including two (*Sa*, *Ssa,* dotted line) and four (*Sa*, *Ssa*, *Sta*, *Sqa*, red curve) harmonics

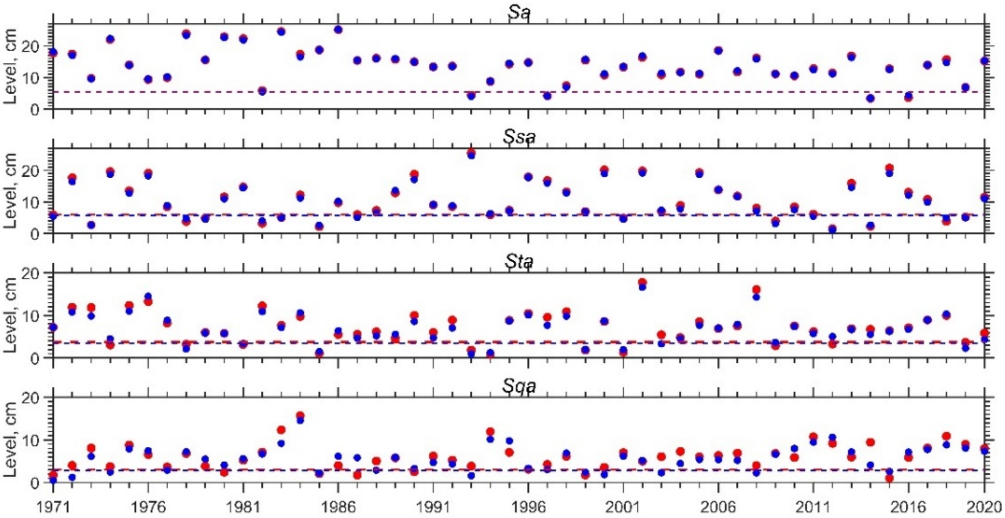
The results shown in Fig. 2 show that only at Frederikshavn station the mean seasonal course of the level is well described by the superposition of harmonics *Sa* and *Ssa*. At other stations, when describing the seasonal behavior by two harmonics, the main minimum shifts from May to April (Rauma, Visby and Oulu stations), and the absence of an intermediate summer maximum in July, associated with the maximum of steric changes in the Baltic level [16] and with an increase in precipitation and river runoff (Gornyy Institut station), or its delay by one month (Rauma, Visby, Oulu and Klaipeda stations). At Klaipeda station, there is also a noticeable discrepancy in the values of the main minimum of the mean seasonal sea level variation when it is described by two harmonics. The superposition of four harmonics, on the contrary, in all cases describes quite well this behavior in different areas of the Baltic (Fig. 2). In this regard, in the present work, all four harmonics were used to describe the mean seasonal variation of the level.

Accuracy of the amplitudes and phases estimated in the stationary approximation of the seasonal sea level fluctuation components was estimated by the method described in [26] as follows. The series of seasonal fluctuations precalculated by formula (1) was subtracted from the initial series of mean daily sea level values. Then the fast Fourier transformation of the residual series was carried out. According to the Fourier analysis results, in the vicinity of the frequency of each seasonal harmonic, the frequency band ω_1, ω_2, …, ω_n and the corresponding amplitude values $A(\omega_1)$, $A(\omega_2)$, …, $A(\omega_n)$ and phases $G(\omega_1)$, $G(\omega_2)$, …, $G(\omega_n)$ were identified. Further, for the obtained estimates of the amplitudes and phases of seasonal harmonics, their rms errors were calculated:

$$\sigma_A = \sqrt{\frac{\sum(A(\omega) - \overline{A(\omega)})^2}{N}} , \tag{2}$$

$$\sigma_G = \frac{\sigma_A}{A} * \frac{180}{\pi} , \tag{3}$$

where σ_A is the rms error of harmonic amplitude calculation; σ_G is the rms error of harmonic phase calculation; N is the series member quantity; $\pi = 3.14$.



F i g. 3. Comparison of the daily and monthly average sea levels at Stockholm station in 1971–2020 resulted from a moving harmonic analysis. Amplitudes of the annual, semiannual, terannual and quarterannual components of seasonal sea level fluctuations are calculated from the daily (red circles) and monthly (blue circles) average data. Dotted line indicates the mean square error in the amplitude calculation

To consider the nonstationarity of seasonal fluctuations, the sea level series were subjected to a moving harmonic analysis [18]. Fig. 3 compares the results of a moving harmonic analysis of the series of monthly and daily average sea level values at Stockholm station with a period of quasi-stationarity (moving window) of one year. It is clearly seen that the greatest agreement in the amplitude estimates for the monthly and mean daily level series is noted for the *Sa* harmonic, although in some rare cases the results of a harmonic analysis of the monthly and mean daily level series for this harmonic differ by 26%. With an increase in the frequency of the annual level variation overtones, these differences increase, reaching the greatest discrepancies in the estimates of the calculated amplitudes for the *Sta* and *Sqa* harmonics (Fig. 3). Such significant discrepancies in the estimates of the amplitudes of the components of seasonal fluctuations are associated with the non-equidistance of the series of monthly mean sea level values [22] and a small number of terms in the series in the sliding window (12), which does not allow a sufficiently accurate description of the interannual variability of the seasonal fluctuations' components. Therefore, in the present work, to carry out a moving harmonic analysis, the series of mean daily sea level values were used.

For the annual harmonic *Sa*, the moving window was taken equal to one year, and the moving harmonic analysis was carried out without overlap (i.e., for each subsequent year). For other harmonics, the moving Fourier analysis was carried out with an overlap.

To isolate the non-stationary semi-annual component *Ssa*, the moving window was taken equal to one year and the sliding was carried out with an overlap every six months; to isolate the terannual harmonic *Sta*, the moving window was taken equal to 8 months and the sliding was carried out every 4 months; to isolate the quarter-annual harmonic *Sqa*, the moving window was taken equal to 6 months, and the sliding was carried out every 3 months. Based on the estimated amplitudes and phases for each sliding period, the series of four components of seasonal fluctuations were precalculated, which were then combined into $\zeta_{sa}(t)$, $\zeta_{ssa}(t)$, $\zeta_{sta}(t)$, $\zeta_{sqa}(t)$ series describing the interannual changes of each component. The rms errors in calculating the amplitudes of harmonics estimated using a moving harmonic analysis were calculated as follows. From the residual series obtained for each slip period, the amplitudes at the frequencies of all four harmonics were estimated. Based on the series of these amplitudes, their standard deviation, taken as the standard error in calculating the amplitudes of the studied harmonics, was determined.

The linear trend significance in the interannual changes in the amplitudes of the harmonics *Sa, Ssa, Sta* and *Sqa* was estimated using the Student's t-test [1].

To study the possible causes of changes in the amplitude of annual sea level fluctuations in the last half century, the series of urgent (4 times a day) instrumental measurements of atmospheric pressure (*Pa*) at Kronstadt station (1979–2020), wind speed and direction (*W*) at Vyborg (1966–2020), Ozerki (1977–2020) and Pionerskij (1977–2020) stations, as well as the data from ship measurements at different horizons of water temperature (*T*) and salinity (*S*) at BY-15 international monitoring station (see Fig. 1) for 1971–2020, obtained from DAS international database (Available at: http://nest.su.se/das/), were used. The initial *Pa* and *W* data were averaged up to one day, and then, using the method described above, a moving harmonic analysis was carried out.

The *T* and *S* data obtained at BY-15 station were used to estimate the temporal changes in sea level steric fluctuations at the annual harmonic *Sa* frequency. For this purpose, for each standard horizon, the series of mean monthly values *T* and *S*, used to calculate sea water density (ρ) according to the equation of state described in [27], were implemented. The steric changes in the level ($\zeta\rho$) were estimated using the calculation formula (4) from [28]:

$$\frac{\Delta\zeta_s}{\Delta t} = -\sum_{i=1}^{n} \frac{1}{\rho} \frac{\Delta\rho_i}{\Delta t} \Delta z_i \ , \tag{4}$$

---

[1] Malinin, V.N., 2008. [*Statistical Methods for the Analysis of Hydrometeorological Information*]. St. Peterburg: RSHU, 408 p. (in Russian).

where $\frac{\Delta\zeta_s}{\Delta t}$ are steric changes in sea level over time Δt; $\frac{\Delta\rho_i}{\Delta t}$ is the change in seawater density in layer i (i = 1, 2, …, n); Δz_i is the difference between the horizons of the i-layer.

The resulting series of mean monthly values of steric fluctuations $\zeta\rho(t)$ was subjected to a sliding harmonic analysis with a sliding period of 12 months.

Based on the results of a sliding harmonic analysis of atmospheric pressure, wind and steric sea level fluctuations, the series of changes in time of *Sa* harmonic of these processes were predicted: $Pa_{sa}(t)$, $W_{sa}(t)$, $\zeta\rho_{sa}(t)$.

To estimate the relationships between changes in time of annual sea level fluctuations, atmospheric pressure, wind and steric fluctuations, a cross-correlation analysis was carried out between anomalies of annual sea level fluctuations $\zeta_{sa}(t)' = \zeta_{sa}(t) - \overline{\zeta_{sa}(t)}$ and annual anomalies $Pa_{sa}(t)' = = Pa_{sa}(t) - \overline{Pa_{sa}(t)}$, $W_{sa}(t)' = W_{sa}(t) - \overline{W_{sa}(t)}$, $\zeta\rho_{sa}(t)' = \zeta\rho_{sa}(t) - \overline{\zeta\rho_{sa}(t)}$, where $\overline{\zeta_{sa}(t)}$, $\overline{Pa_{sa}(t)}$, $\overline{W_{sa}(t)}$, $\overline{\zeta\rho_{sa}(t)}$ are stationary *Sa* components of hydrometeorological processes. The transition to anomalies was caused by the fact that in all hydrometeorological processes a stationary annual component is well expressed, and it has a noticeable effect on the results of cross-correlation analysis [29].

A mutual correlation analysis was carried out between the calculated anomalies of annual sea level fluctuations $\zeta_{sa}(t)'$ and anomalies $Pa_{sa}(t)'$, $W_{sa}(t)'$, $\zeta\rho_{sa}(t)'$.

Given that wind fluctuations are a vector process, the relationship estimation between the anomalies $\zeta_{sa}(t)'$ and $W_{sa}(t)'$ by calculating multiple correlation coefficients using the method of cross-correlation analysis between scalar and vector processes [2] was carried out. Following this technique, first the matrices of cross-correlation coefficients of the following form were evaluated:

$$D_{\eta V} = \begin{vmatrix} r_{\eta\eta} & r_{\eta u} & r_{\eta v} \\ r_{u\eta} & r_{uu} & r_{uv} \\ r_{v\eta} & r_{\eta u} & r_{vv} \end{vmatrix}, D_{uv} = \begin{vmatrix} r_{uu} & r_{uv} \\ r_{vu} & r_{vv} \end{vmatrix}, \qquad (5)$$

where $D_{\eta V}$ and D_{uv} are matrix determinants; η is a scalar process; V is a vector process; u, v are the components of the vector process per parallel and meridian, respectively $r_{\eta\eta}$, $r_{\eta u}$, r_{uv}, …, r_{vv} are cross-correlation coefficients.

Then the multiple correlation coefficient between the scalar (η) and vector (V) processes was calculated:

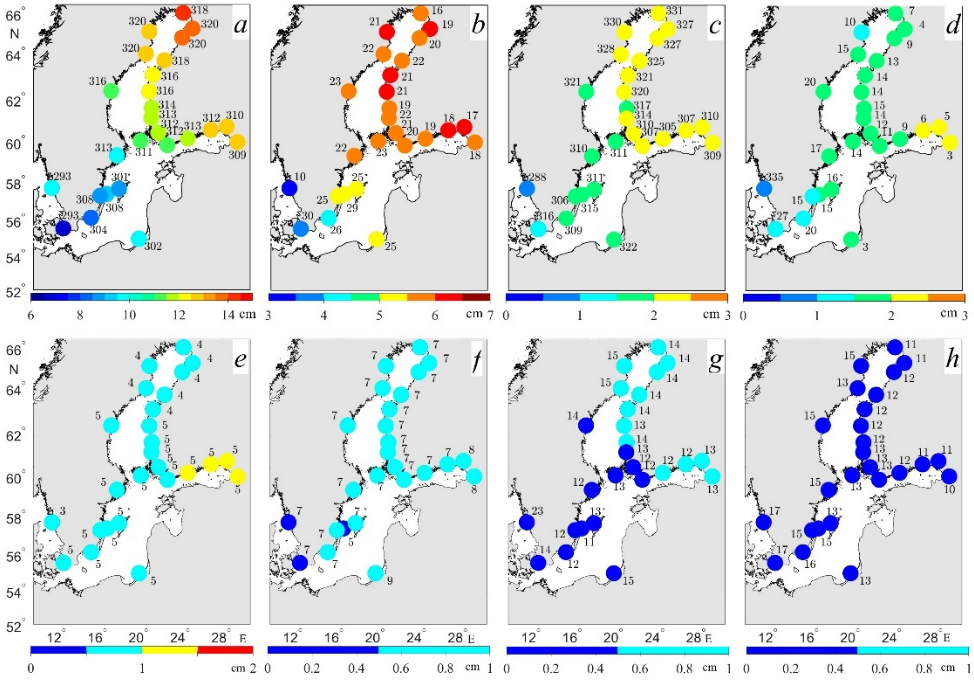
$$R_{\eta V} = \sqrt{1 - \frac{D_{\eta V}}{D_{uv}}}\,. \qquad (6)$$

---

[2] Rozhkov, V.A., 2002. *Theory and Methods of Statistical Estimation of Probability Characteristics of Random Variables and Functions with Hydrometeorological Examples.* St. Petersburg: Gidrometeoizdat. Vol. 2, 780 p. (in Russian).

Results and their interpretation

Fig. 4 shows the results of a stationary harmonic analysis of the series of mean daily values of the Baltic Sea level. They show that at the considered tide gauge Baltic Sea stations, the average amplitudes of the harmonics *Sa, Ssa, Sta* and *Sqa* are distinguished reliably. The minimum amplitude of the seasonal level fluctuations of 6.4 cm with a year period is observed in the Baltic southwest at the exit from the Sound Strait (Klagshamn station) (Fig. 4, *a*). In the north of the Kattegat Strait (Gothenburg station), the *Sa* amplitude increases to 9.6 cm at Oskarshamn station, up to 9.9 cm – at Pionerskij station in the open Baltic, up to 11.6–12.9 cm in the Gulf of Finland (Hanko and Vyborg stations) and reaches maximum values of 14.5 cm in the very north of the Gulf of Bothnia (Kemi station) (Fig. 4, *a*). The estimates of spatial variations in the *Sa* harmonic phase are statistically significant, and they indicate that, first, the maximum of annual sea level fluctuations occurs in October in the southwest of the Baltic (Klagshamn station), and then spreads to the north and northeast of the sea, where it is noted in November. Compared with the previous twenty years 1951–1970 [1] in the period under consideration, the *Sa* harmonic amplitudes increased by 0.9–2.2 cm, and the maximum of annual fluctuations start to appear 1–2 months later.



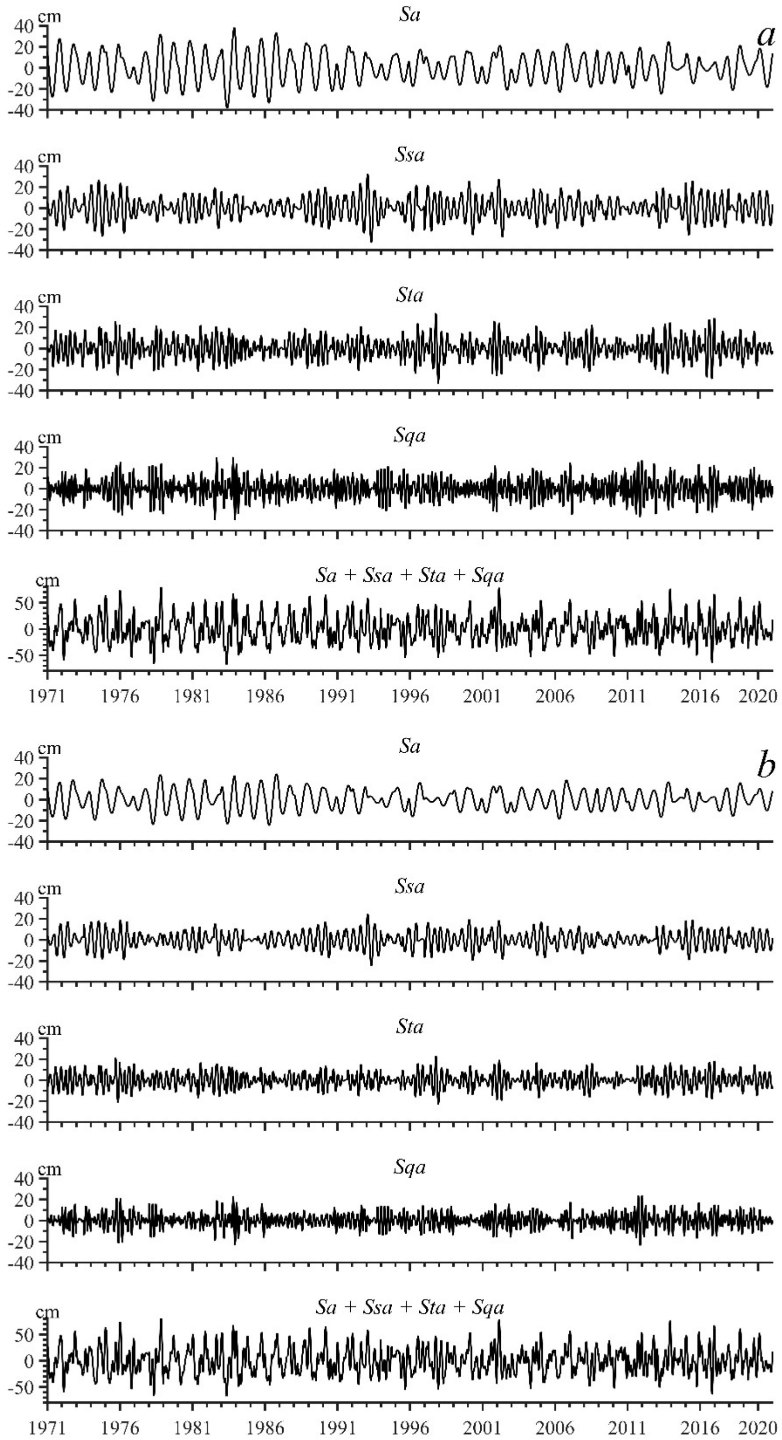
F i g. 4. Amplitude-phase characteristics of the annual (*a*), semi-annual (*b*), terannual (*c*) and quarter-annual (*d*) components of seasonal fluctuations of the Baltic Sea level in 1971–2020 estimated from the tide gauge data obtained at the coastal stations; root-mean-square errors in the amplitude and phase estimates of the annual (*e*), semi-annual (*f*), terannual (*g*) and quarter-annual (*h*) harmonics. Colored circles denote the amplitude (cm), numbers – the phase (º).

The semi-annual harmonic *Ssa* has the mean amplitudes of 1.6–3.2 times less than that of *Sa*. Their smallest values, reaching 3.0 cm, are observed in the north of the Kattegat Strait (Gothenburg station) (Fig. 4, *b*). In the southwest of the open Baltic, the *Ssa* amplitude slightly increases to 3.3 cm (Klagshamn station) and continues to grow when moving to the north and northeast, reaching the maximum values of 6.25 cm in the northeast of the Gulf of Finland (Hamina station). A statistically significant change in the phase of semi-annual fluctuations is noted only in the Kattegat Strait, where it increases in the southeast direction by 20°. In the open Baltic, the Gulfs of Bothnia and Finland, the phase changes are insignificant and comparable with the standard errors of their estimation (Fig. 4, *b*).

The mean amplitudes of the terannual (*Sta*) and quarterannual (*Sqa*) harmonics are much less than the amplitudes of the *Sa* and *Ssa* harmonics, they vary from 0.83–0.84 cm in the north in the Kattegat Strait (Gothenburg station) to the maximum values of 2.55–2.57 cm in the east of the Gulf of Finland (Fig. 4, *c*, *d*). In the vast majority of cases, the *Sta* amplitudes are greater than *Sqa*, especially in the north of the Gulf of Bothnia, where they exceed the *Sqa* amplitudes by 1.5 times. Only in the north of the Kattegat Strait (Gothenburg station) and in the southeast of the open Baltic (Pionerskij station) is the *Sta* amplitude slightly less than the *Sqa* amplitude (Fig. 4 *c*, *d*). The estimates of these harmonics' phase have large standard errors of calculation, which are comparable to or exceed the spatial variations in the phase of these seasonal sea level fluctuation components (Fig. 4, *g*, *h*).

A comparison with the results of harmonic analysis from [6], which considered longer series of average monthly levels, covering periods from the early 1800s, 1900s until 2012, shows an increase in the amplitudes of all four harmonics over the past half century. A particularly significant increase in amplitude (by a factor of 2–6) is noted for the *Sta* harmonic.

Fig. 5 shows examples of the series of seasonal sea level fluctuation components $\zeta_{sa}(t)$, $\zeta_{ssa}(t)$, $\zeta_{sta}(t)$, $\zeta_{sqa}(t)$, as well as their superposition in the Gulf of Finland (Kronstadt station) and in the open Baltic (Visby station), estimated using a moving harmonic analysis. There is a significant interannual variability of amplitudes for all four components. In some years, their amplitudes reach 20–40 cm; in other years, they decrease to several centimeters. At Kronstadt station, the largest *Sa* harmonic amplitude was observed in 1983. That year, the largest number of floods in the history of St. Petersburg (10 cases) occurred. In the time course of the amplitudes of the *Sa, Ssa, Sta* and *Sqa* components, the amplitude modulation is well traced. The annual component has a modulation period of ~ 20 years. A similar feature in the changes in the annual fluctuations of the Baltic Sea level was noted by the authors of [20] based on the analysis results of series of mean monthly values of tide gauge data received using a discrete wavelet transformation. For the *Ssa*, *Sta* and *Sqa* components, the modulation period varies approximately in the range of 2–10 years (Fig. 5).



F i g. 5. The series of sea level seasonal fluctuation components *Sa*, *Ssa*, *Sta*, *Sqa* and their superpositions *Sa* + *Ssa* + *Sta* + *Sqa* in Kronstadt (*a*) and in Visby (*b*) obtained using a moving harmonic analysis

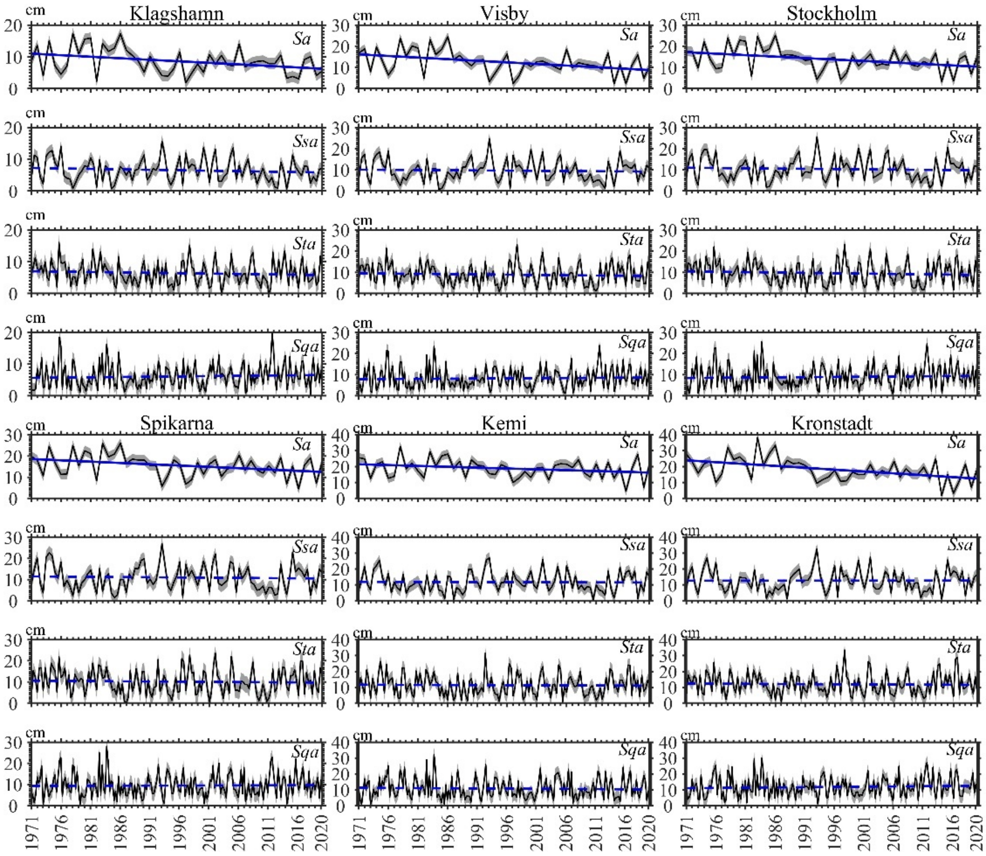
Fig. 6 shows the interannual changes in the amplitudes of the *Sa*, *Ssa*, *Sta* and *Sqa* harmonics for 1971–2020 at tide gauge stations of the Baltic Sea. Significant negative trends are noted for the *Sa* harmonic at all stations, indicating that in the past half century in various parts of the Baltic Sea, the amplitude of the annual seasonal level fluctuation component has decreased. The largest trend decrease in the *Sa* harmonic amplitude is noted at Kronstadt station, where it decreased by 11.5 cm over half a century. Unlike the *Sa* harmonic, there are no significant linear trends in the interannual variability of the *Ssa*, *Sta* and *Sqa* harmonic amplitudes.

The presence of a significant negative trend in the *Sa* harmonic variation (Fig. 6) contradicts the results of [16], whose authors identified a significant positive trend in the interannual variations in the annual harmonic amplitude at Stockholm station in 1825–1984. These differences in the trend signs may be due to the fact that over the past two centuries there have been multidirectional trends in the interannual changes in the amplitudes of the annual seasonal fluctuation component in the Baltic Sea level. Continuous sea level measurements at Stockholm station allow a more detailed study of the interannual variability of the annual harmonic amplitude, taking into account the past decades.

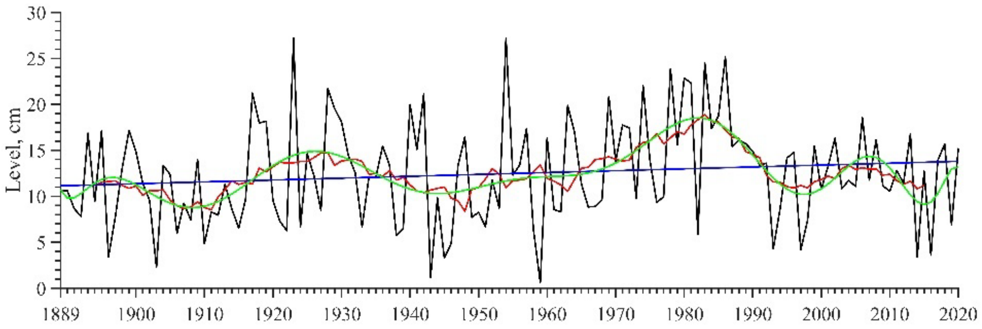
Table 2 shows the results of a cross-correlation analysis of interannual changes in the amplitude of the annual seasonal fluctuation component in the areas of operation of various tide gauges, which demonstrate a high correlation between changes in the amplitudes of annual level fluctuations in different sea areas. The cross-correlation coefficients vary within 0.6–1.0, at Stockholm station – within 0.8–1.0. These results show that changes in the amplitude of annual fluctuations at Stockholm station reflect its interannual changes throughout the Baltic Sea well.

Fig. 7 shows the time variations in the amplitude of annual sea level fluctuations at Stockholm station in 1889–2020 estimated using moving harmonic analysis. In contrast to work [16], where for an earlier period of 1825–1984 a significant positive trend was obtained in changes in the amplitude of annual sea level fluctuations at Stockholm station, in the studied period, there is already a statistically insignificant positive trend here. It may indicate that in the 132-year period we consider, there have been noticeable changes in the regime of hydrometeorological processes that determine interannual changes in annual sea level fluctuations. Multidirectional tendencies are observed in changes in the *Sa* harmonic amplitude. The most significant increase in the amplitude of annual sea level fluctuations was noted in the periods from 1900s – mid-1920s and from 1940s – early 1980s, when the maximum amplitudes reached 25–27 cm. From the mid-1880s until the end of the 1890s and from the 1920s until the early 1940s, there was a noticeable decrease in the *Sa* harmonic amplitude, when in some years its values decreased to 1.5–2.5 cm. A significant undulating decrease in the amplitude of annual fluctuations has been observed from the 1980s until present.

There is the question of the physical mechanisms of such significant changes over time in the characteristics of annual fluctuations in the Baltic Sea level and, in particular, about the reasons for the significant negative trend in the variations in their amplitudes over the past half century (Fig. 6).



F i g. 6. Interannual changes in the amplitudes of four seasonal level fluctuation components at different coastal stations in the Baltic Sea (black curves). Gray color shows the root-mean-square error in the amplitude calculation, the blue solid and dashed straight lines are the significant and insignificant linear trends



F i g. 7. Interannual changes in the annual component amplitude of the seasonal sea level fluctuations in Stockholm in 1889–2020 (black curve), linear trend (blue strait line), the 15th grade polynomial (green curve), 11-year moving average (red curve)

T a b l e 2

Correlation coefficients between the changes in the annual component amplitude of the sea level seasonal fluctuations at different tide gauge stations. The station names correspond to the numbers in Fig. 1

No	Station numbers (No)																			
	21	11	2	24	23	17	12	3	4	5	15	14	10	19	9	8	20	7	26	29
21	1.0	0.9	0.8	1.0	1.0	1.0	0.8	0.9	1.0	1.0	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9
11	0.9	1.0	0.7	0.9	0.9	1.0	0.9	0.7	0.8	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.8
2	0.8	0.7	1.0	0.8	0.7	0.8	0.6	0.8	0.8	0.8	0.7	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.7
24	1.0	0.9	0.8	1.0	1.0	1.0	0.8	0.8	0.9	0.9	0.9	0.9	0.9	1.0	0.9	1.0	1.0	0.9	1.0	0.9
23	1.0	0.9	0.7	1.0	1.0	1.0	0.8	0.8	0.9	1.0	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	0.9
17	1.0	1.0	0.8	1.0	1.0	1.0	0.9	0.8	0.9	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1,0	0.9	0.9	0.8
12	0.8	0.9	0.6	0.8	0.8	0.9	1.0	0.6	0.7	0.8	0.9	1.0	0.9	0.9	0.9	0.8	0.9	0.8	0.8	0.7
3	0.9	0.7	0.8	0.8	0.8	0.8	0.6	1.0	1.0	0.9	0.7	0.7	0.7	0.8	0.8	0.9	0.9	0.9	0.8	0.8
4	1.0	0.8	0.8	0.9	0.9	0.9	0.7	1.0	1.0	1.0	0.8	0.8	0.8	0.9	0.9	1.0	0.9	1.0	0.9	0.9
5	1.0	0.9	0.8	0.9	1.0	0.9	0.8	0.9	1.0	1.0	0.9	0.8	0.9	1.0	0.9	1.0	1.0	1.0	0.9	0.9
15	0.9	1.0	0.7	0.9	0.9	1.0	0.9	0.7	0.8	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.8
14	0.9	1.0	0.7	0.9	0.9	1.0	1.0	0.7	0.8	0.8	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.8	0.9	0.8
10	0.9	1.0	0.7	0.9	0.9	1.0	0.9	0.7	0.8	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9	0.9	0.8
19	1.0	1.0	0.8	1.0	1.0	1.0	0.9	0.8	0.9	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9
9	1.0	1.0	0.8	0.9	1.0	1.0	0.9	0.8	0.9	0.9	1.0	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.8
8	1.0	0.9	0.8	1.0	1.0	1.0	0.8	0.9	1.0	1.0	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9
20	1.0	0.9	0.8	1.0	1.0	1.0	0.9	0.9	0.9	1.0	0.9	0.9	0.9	1.0	1.0	1.0	1.0	1.0	0.9	0.9
7	1.0	0.9	0.8	0.9	1.0	0.9	0.8	0.9	1.0	1.0	0.9	0.8	0.9	1.0	0.9	1.0	1.0	1.0	0.9	0.9
26	0.9	0.9	0.7	1.0	1.0	0.9	0.8	0.8	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	0.9
29	0.9	0.8	0.7	0.9	0.9	0.8	0.7	0.8	0.9	0.9	0.8	0.8	0.8	0.9	0.8	0.9	0.9	0.9	0.9	1.0

N o t e. See the station names corresponding to the numbers, in Fig. 1.

The study of sea level seasonal fluctuation causes should be based on theoretical concepts of the large-scale fluctuation mechanisms. These mechanisms are most fully described based on the analysis of the formalized hydrostatic equation [30], as well as the depth-integrated mass continuity equation [31, 32]. In these equations, the rate of sea level change is related to variations in dynamic, steric and water balance processes. The influence of dynamic processes on changes in seasonal sea level fluctuations is determined by seasonal changes in atmospheric pressure and wind [30–32]. The steric component of seasonal sea level disturbances is associated with seasonal changes in seawater density [30]. The Baltic Sea level fluctuations, caused by changes in the water balance, are determined by seasonal changes in atmospheric precipitation, continental runoff, evaporation and water exchange with the North Sea [32].

To study the reasons for the annual fluctuation nonstationarity in the Baltic Sea level, the cross-correlation and regression analyzes of sea level fluctuations with various hydrometeorological processes were used [2, 18, 19, 21, 33]. The results presented in the listed papers showed that there was a high correlation between changes in time of annual fluctuations in sea level and zonal wind, atmospheric pressure and air temperature, while there was no correlation with fluctuations in river runoff [21]. The regression analysis also showed the decisive contribution of wind and atmospheric pressure fluctuations to the description of the interannual variability of seasonal fluctuations in the Baltic Sea level [20, 33].

In [29], for a more representative assessment of the correlation between long-term changes in the seasonal fluctuation components of the Baltic Sea level, estimated from satellite altimetry data and various hydrometeorological processes, it was proposed to pass to their anomalies by excluding the stationary component from the series of non-stationary components of seasonal sea level fluctuations and other processes obtained with the help of moving harmonic analysis. The results of such an analysis indicated that for all four harmonics (*Sa, Ssa, Sta* and *Sqa*) there was no relationship between sea level anomalies and freshwater balance components (precipitation, evaporation and continental runoff), while a high correlation was noted with wind and atmospheric pressure anomalies [29]. In addition, for the *Sa* harmonic there was a high correlation with annual air temperature anomalies (which may be associated with thermosteric sea level fluctuations) and with annual anomalies of water transport through the Danish Straits, the correlation coefficients were low. For the *Ssa, Sta* and *Sqa* harmonics, on the contrary, high correlation coefficients were noted between seasonal anomalies of sea level and water transport [29].

Taking into account the results of the above mentioned works, it can be assumed that significant negative trends in changes in the annual level fluctuation amplitudes observed over the past half century must be associated with changes in annual fluctuations of wind, atmospheric pressure and seawater density.

Fig. 8 shows the interannual variations in the amplitudes of the *Sa* harmonic of atmospheric pressure and wind at hydrometeorological stations in the Baltic Sea, as well as steric level fluctuations at station BY-15, obtained from the moving harmonic analysis results. It is clearly seen that, just as with the changes in annual sea level fluctuations (Fig. 6), significant negative trends in changes in the amplitude of annual fluctuations in atmospheric pressure and wind have been observed in the past half century (Fig. 8, *a*, *b*). The cross-correlation analysis results given below show that between the changes in annual sea level anomalies $\zeta_{sa}(t)'$ and atmospheric pressure $Pa_{sa}(t)'$, as well as wind variability $W_{sa}(t)'$ at different stations, there are high values of correlation coefficients, reaching 0.66–0.78, which is in good agreement with the results of other works [2, 18, 19, 21, 33]. However, in variations in the amplitude of steric fluctuations with a year period, on the contrary, a significant positive trend is observed (Fig. 8, *c*).

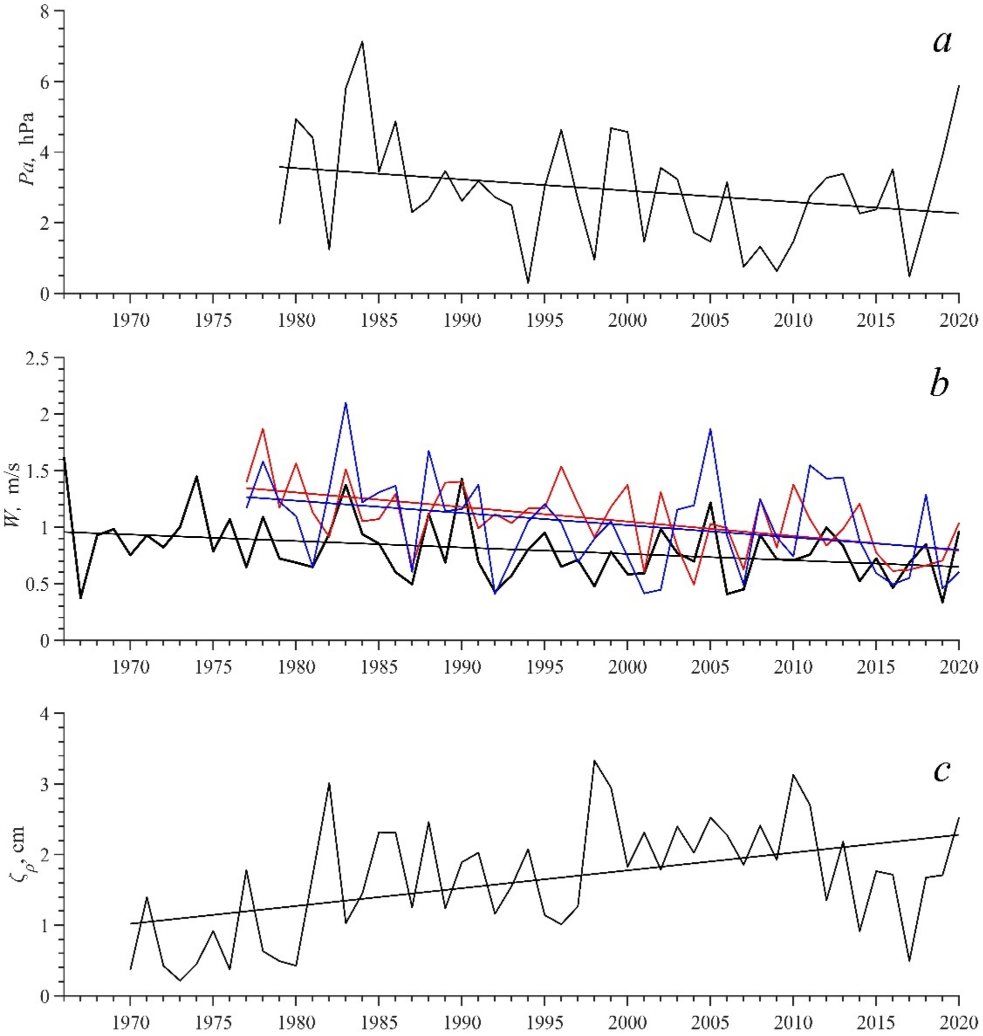


Fig. 8. Interannual changes in the amplitude of seasonal fluctuations annual component in the atmospheric pressure in Kronstadt (*a*), wind speed at the hydrometeorological stations Vyborg (black curve), Ozerki (red curve), Pionerskij (blue curve) (*b*), and steric fluctuations of the sea level at station BY-15 (*c*). Straight lines are the significant linear trends

Below, there are maximum values of correlation coefficients R and time shifts τ (in brackets) between the anomalies of annual sea level fluctuations $\zeta_{sa}(t)'$ and annual anomalies of atmospheric pressure $Pa_{sa}(t)'$, wind $W_{sa}(t)'$ and steric level fluctuations $\zeta\rho_{sa}(t)'$ in different areas of the Baltic:

$\zeta_{sa}(t)'$ at Kronstadt station – $Pa_{sa}(t)'$ at Kronstadt station – 0.74 (0)
$\zeta_{sa}(t)'$ at Kronstadt station – $W_{sa}(t)'$ at Ozerki station – 0.67 (0)
$\zeta_{sa}(t)'$ at Pionerskij station – $W_{sa}(t)'$ at Pionerskij station – 0.78 (0)
$\zeta_{sa}(t)'$ at Vyborg station – $W_{sa}(t)'$ at Vyborg station – 0.66 (0)
$\zeta_{sa}(t)'$ at Visbi station – $\zeta\rho_{sa}(t)'$ at station BY-15 – 0.09 (–1)
$\zeta_{sa}(t)'$ at Klaipeda station – $\zeta\rho_{sa}(t)'$ at station BY-15 – 0.16 (–1).

The range of changes in the annual atmospheric pressure fluctuation amplitudes at Kronstadt station reaches 6.7 hPa (0.3–7.0 hPa), and their trend decrease is 1.3 hPa (Fig. 8, *a*). According to the “reverse barometer” law, such changes in the atmospheric pressure correspond to variations in static sea level fluctuations in the range of 0.3–7.0 cm and 1.3 cm in trend changes. Although these are noticeable level changes, they are not decisive for explaining the total changes in sea level amplitudes for the *Sa* harmonic at Kronstadt station, where $\zeta_{sa}(t)$ amplitudes vary in the range of 1.8–38.3 cm, and their trend decrease is 11.5 cm (23.9–12.4 cm) (Fig. 6).

The maximum amplitude of steric $\zeta\rho_{sa}(t)$ level oscillations at station BY-15 is very small (3.3 cm), and it is more than half the size of the amplitude of annual static level fluctuations (Fig. 8). The maximum amplitude of the total annual level fluctuations $\zeta_{sa}(t)$ at the nearest Visby station reaches 24.4 cm. The cross-correlation analysis between the anomalies $\zeta_{sa}(t)'$ at Visby and Klaipeda stations with the anomalies $\zeta\rho_{sa}(t)'$ at station BY-15 shows a lack of communication between these processes. These results indicate that interannual changes in annual steric sea level fluctuations cannot be the reason for the significant decreases in the amplitudes of the *Sa* harmonic observed in the past half century (Fig. 6).

Taking into account the fact that previous works showed the absence of a stationary relationship between $\zeta_{sa}(t)'$ anomalies and annual anomalies of the water balance components [21, 29], the results obtained here suggest that the main reason for the significant decreases in the amplitude of annual fluctuations of the Baltic Sea levels observed in the past half century is a decrease in the amplitudes of annual fluctuations of the wind and, to a lesser extent, of atmospheric pressure.

Conclusions

1. Based on the stationary harmonic analysis, it is shown that the average seasonal course of the level in the coastal Baltic is most accurately described by the superposition of not two (*Sa* and *Ssa*), but four harmonics: annual (*Sa*), semi-annual (*Ssa*), terannual (*Sta*) and quarter-annual *Sqa*.

2. For a more accurate assessment of the seasonal sea level fluctuation non-stationarity using a moving harmonic analysis, it is necessary to use the series of daily mean rather than monthly sea level values.

3. The results of the stationary harmonic analysis of the series of mean daily values of tide gauge data at 26 stations of the Baltic Sea showed an increase in the average amplitude of the components of seasonal *Sa, Ssa, Sta* and *Sqa* sea level fluctuations in the past half century compared to the previous decades.

4. Average *Sa* harmonic amplitudes in 1971–2020 vary from 6.5 cm in the southwest of the Baltic Sea to 14.5 cm in the very north of the Gulf of Bothnia. The second largest *Ssa* harmonic has average amplitudes from 3 cm in the north of the Kattegat Strait up to 6.25 cm in the northeast of the Gulf of Finland. The average amplitudes of the terannual (*Sta*) and quarterannual (*Sqa*) harmonics are much less than the amplitudes of *Sa* and *Ssa* harmonics and vary from 0.83–0.84 cm in the north of the Kattegat Strait (Gothenburg station) to the maximum values of 2.55–2.57 cm in the east of the Gulf of Finland.

5. The moving harmonic analysis results show a significant non-stationarity of all four components of seasonal fluctuations with a pronounced amplitude modulation. The annual *Sa* component has a modulation period of approximately 20 years. For *Ssa, Sta* and *Sqa* components, the modulation period varies from approximately 2 to 10 years.

6. The interannual changes in the amplitude of *Sa* harmonic in different areas of the Baltic Sea are well interconnected and have significant negative trends in 1971–2020.

7. The estimation of the nonstationarity of *Sa* harmonic at Stockholm station, carried out based on the moving harmonic analysis of a longer series of mean daily sea level values in 1889–2020, demonstrates an insignificant positive trend, against which the multidirectional trends in changes of *Sa* harmonic amplitude are observed. The most significant increase in the amplitude of annual sea level fluctuations was noted in periods from the 1900s until the end of the 1920s and from the 1940s until the early 1980s. From the beginning of the 1920s until the early 1940s and from the early 1980s to date, there has been a significant decrease in the amplitude of annual fluctuations, when in some years the amplitude values decreased to 1.5–4.0 cm.

8. It is shown that the main reason for the significant decrease in the amplitudes of annual fluctuations in the Baltic Sea level observed in the past half century is the decrease in the amplitudes of annual fluctuations of wind and, to a lesser extent, atmospheric pressure.

REFERENCES

1. Terziev, F.S., Rozhkov, V.A. and Smirnova, A.I., eds., 1992. [*Hydrometeorology and Hydrochemistry of the Seas of USSR. Vol. III, The Baltic Sea. Part I, Hydrometeorological Conditions*]. Leningrad: Gidrometeoizdat, 456 p. (in Russian).
2. Cheng, Y., Xu, Q. and Li, X., 2018. Spatio-Temporal Variability of Annual Sea Level Cycle in the Baltic Sea. *Remote Sensing,* 10(4), 528. doi:10.3390/rs10040528

3. Männikus, R., Soomere, T. and Viška, M., 2020. Variations in the Mean, Seasonal and Extreme Water Level on the Latvian Coast, the Eastern Baltic Sea, during 1961–2018. *Estuarine, Coastal and Shelf Science*, 245, 106827. doi:10.1016/j.ecss.2020.106827
4. Lisitzin, E., 1974. *Sea-Level Changes.* Amsterdam: Elsevier, 285 p.
5. Ekman, M., 1996. A Common Pattern for Interannual and Periodical Sea Level Variations in the Baltic Sea and Adjacent Waters. *Geophysica,* 32(3), pp. 261-272.
6. Medvedev, I.P., 2014. Seasonal Fluctuations of the Baltic Sea Level. *Russian Meteorology and Hydrology*, 39(12), pp. 814-822. doi:10.3103/S106837391412005X
7. Łabuz, T.A. and Kowalewska-Kalkowska, H., 2011. Coastal Erosion Caused by the Heavy Storm Surge of November 2004 in the Southern Baltic Sea. *Climate Research*, 48(1), pp. 93-101. doi:10.3354/cr00927
8. Weisse, R., Dailidiene, I., Hünicke, B., Kahma, K., Madsen, K., Omstedt, A., Parnell, K., Schöne, T., Soomere, T. [et al.], 2021. Sea Level Dynamics and Coastal Erosion in the Baltic Sea Region. *Earth System Dynamics*, 12(3), pp. 871-898. doi:10.5194/esd-12-871-2021
9. Ekman, M., 2009. *The Changing Level of the Baltic Sea during 300 Years: A Clue to Understanding the Earth.* Åland Islands: Summer Institute for Historical Geophysics, 155 p.
10. Gustafsson, B.G. and Andersson, H.C., 2001. Modeling the Exchange of the Baltic Sea from the Meridional Atmospheric Pressure Difference across the North Sea. *Journal of Geophysical Research: Oceans*, 106 (C9), pp. 19731-19744. doi:10.1029/2000JC000593
11. Samuelsson, M. and Stigebrandt, A., 1996. Main Characteristics of the Long-Term Sea Level Variability in the Baltic Sea. *Tellus A: Dynamic Meteorology and Oceanography*, 48(5), pp. 672-683. doi:10.3402/TELLUSA.V48I5.12165
12. Gordeeva, S.M. and Malinin, V.N., 2014. *Gulf of Finland Sea Level Variability.* St. Petersburg: RSHU Publishers, 179 p. (in Russian).
13. Zakharchuk, E.A. and Tikhonova, N.A., 2011. On the Spatiotemporal Structure and Mechanisms of the Neva River Flood Formation. *Russian Meteorology and Hydrology,* 36(8), 534. doi:10.3103/S106837391108005X
14. Wübber, C. and Krauss, W., 1979. The Two-Dimensional Seiches of the Baltic Sea. *Oceanologoca Acta,* 2(4), pp. 435-446. Available at: https://archimer.ifremer.fr/doc/00122/23360/ [Accessed: 27 December 2022]
15. Zakharchuk, E.A., Tikhonova, N.A., Zakharova, E. and Kouraev, A.V., 2021. Spatiotemporal Structure of Baltic Free Sea Level Oscillations in Barotropic and Baroclinic Conditions from Hydrodynamic Modelling. *Ocean Science*, 17(2), pp. 543-559. doi:10.5194/os-17-543-2021
16. Ekman, M. and Stigebrandt, A., 1990. Secular Change of the Seasonal Variation in Sea Level and of the Pole Tide in the Baltic Sea. *Journal of Geophysical Research: Oceans*, 95(C4), pp. 5379-5383. doi:10.1029/JC095iC04p05379
17. Ekman, M., 1998. Secular Change of the Seasonal Sea Level Variation in the Baltic Sea and Secular Change of the Winter Climate*.* *Geophysica,* 34(3), pp. 131-140.
18. Plag, H.-P. and Tsimplis, M.N., 1999. Temporal Variability of the Seasonal Sea-Level Cycle in the North Sea and Baltic Sea in Relation to Climate Variability. *Global and Planetary Change*, 20(2-3), pp. 173-203. https://doi.org/10.1016/S0921-8181(98)00069-1
19. Hünicke, B. and Zorita, E., 2008. Trends in the Amplitude of Baltic Sea Level Annual Cycle. *Tellus A: Dynamic Meteorology and Oceanography,* 60(1), pp. 154-164. doi:10.1111/j.1600-0870.2007.00277.x
20. Barbosa, S.M. and Donner, R.V., 2016. Long-Term Changes in the Seasonality of Baltic Sea Level. *Tellus A: Dynamic Meteorology and Oceanography*, 68(1), 30540. doi:10.3402/tellusa.v68.30540
21. Stramska, M., Kowalewska-Kalkowska, H. and Świrgoń, M., 2013. Seasonal Variability in the Baltic Sea Level. *Oceanologia*, 55(4), pp. 787-807. doi:10.5697/oc.55-4.787

22. Cartwright, D.E., 1983. On the Smoothing of Climatological Time Series, with Application to Sea-Level at Newlyn. *Geophysical Journal International*, 75(3), pp. 639-658. https://doi.org/10.1111/j.1365-246X.1983.tb05003.x
23. Holgate, S.J., Matthews, A., Woodworth, P.L., Rickards, L.J., Tamisiea, M.E., Bradshaw, E., Foden, P.R., Gordon, K.M., Jevrejeva, S. and Pugh, J., 2012. New Data Systems and Products at the Permanent Service for Mean Sea Level. *Journal of Coastal Research*, 29(3), pp. 493-504. doi:10.2112/JCOASTRES-D-12-00175.1
24. Volkov, V.A., Johannessen, O.M., Borodachov, V.E., Voinov, G.N., Pettersson, L.H., Bobylev, L.P. and Kouraev, A.V., 2002. Tides and Tidal Streams. In: V. A. Volkov, O. M. Johannessen, V. E. Borodachov, G. N. Voinov, L. H. Pettersson, L. P. Bobylev and A. V. Kouraev, 2002. *Polar Seas Oceanography. An Integrated Case Study of the Kara Sea.* London, UK: Springer. Chapter 5, pp. 147-215.
25. Pajak, K. and Kowalczyk, K., 2019. A Comparison of Seasonal Variations of Sea Level in the Southern Baltic Sea from Altimetry and Tide Gauge Data. *Advances in Space Research*, 63(5), pp. 1768-1780. doi:10.1016/J.ASR.2018.11.022
26. Pugh, D.T., 1987. *Tides, Surges and Mean Sea-Level*. Chichester, UK: John Wiley & Sons, 472 p.
27. Jackett, D.R. and Mcdougall, T.J., 1995. Minimal Adjustment of Hydrographic~~static~~ Profiles to Achieve Static Stability. *Journal of Atmospheric and Oceanic Technology*, 12(2), pp. 381-389. https://doi.org/10.1175/1520-0426(1995)012<0381:MAOHPT>2.0.CO;2
28. Belonenko, T.V. and Koldunov, A.V., 2006. Steric Oscillations of the Sea Level in the North-Western Pacific. *Vestnik of Saint-Petersburg University. Series 7. Geology. Geography*, (3), pp. 81-87 (in Russian).
29. Zakharchuk, E.A., Sukhachev, V.N., Tikhonova, N.A., Kouraev, A. and Zakharova, E., 2022. Seasonal Fluctuations in Baltic Sea Level Determined from Satellite Altimetry. *Continental Shelf Research*, 249, 104863. https://doi.org/10.1016/j.csr.2022.104863
30. Gill, A.E. and Niller, P.P., 1973. The Theory of the Seasonal Variability in the Ocean. *Deep Sea Research and Oceanographic Abstracts,* 20(2), pp. 141-177. doi:10.1016/0011-7471(73)90049-1
31. Foux, V.R., 2003. Hydrodynamic Bases of Interpretation of Altimetric Surveys of the Sea Surface. *Sea Level Fluctuations*. St. Petersburg: RGGMU, pp. 79-91 (in Russian).
32. Leppäranta, M. and Myrberg, K., 2009. *Physical Oceanography of the Baltic Sea*. Berlin, Heidelberg: Springer, 378 p. doi:10.1007/978-3-540-79703-6
33. Johansson, M.M. and Kahma, K.K., 2016. On the Statistical Relationship between the Geostrophic Wind and Sea Level Variations in the Baltic Sea. *Boreal Environment Research*, 21, pp. 25-43.

About the authors:

Evgeny A. Zakharchuk, Head of the Department of Oceanology, St. Petersburg State University (33-35, 10 Line V.O., St. Petersburg, 199178, Russian Federation); Director of the St. Petersburg Branch, N. N. Zubov State Oceanographic Institute (38 Bering St., St. Petersburg, 199026, Russian Federation), Dr.Sci. (Geogr.), **ORCID ID: 0000-0001-6079-5739**, **ResearcherID: N-1644-2013**, **Scopus Author ID: 6603158329**, **SPIN-код: 7724-4240**, eazakharchuk@yandex.ru

Natalya A. Tikhonova, Associate Professor, Department of Oceanology, St. Petersburg State University (33-35, 10 Line V.O., St. Petersburg, 199178, Russian Federation); Head of the Laboratory of the St. Petersburg Branch, N. N. Zubov State Oceanographic Institute (38 Bering St., St. Petersburg, 199026, Russian Federation), Ph.D. (Geogr.), **ORCID ID: 0000-0002-4546-4920**, **ResearcherID: I-4647-2015**, **Scopus Author ID: 11239410500**, **SPIN-код: 9870-7279**, i@ntikhonova.ru

Vladimir N. Sukhachev, Research Associate of Institute of Geosciences, St. Petersburg State University (33-35, 10 Line V.O., St. Petersburg, 199178, Russian Federation); Research Associate of the St. Petersburg Branch, N. N. Zubov State Oceanographic Institute (38 Bering St., St. Petersburg, 199026, Russian Federation), **ORCID ID: 0000-0003-4821-4342**, **ResearcherID: N-7470-2015**, **Scopus Author ID**: **55969236600**, **SPIN-код: 4963-7802,** syhachev@mail.ru

Ekaterina N. Litina, Research Associate of Institute of Geosciences, St. Petersburg State University(33-35, 10 Line V.O., St. Petersburg, 199178, Russian Federation); Research Associate of the St. Petersburg Branch, N. N. Zubov State Oceanographic Institute(38 Bering St., St. Petersburg, 199026, Russian Federation), **ORCID ID: 0000-0003-1069-1768**, **ResearcherID: I-4667-2015**, **Scopus Author ID**: **56534229800**, **SPIN-код: 1777-7640**, warzuga@yandex.ru

Contribution of the co-authors:

Evgeny A. Zakharchuk – interpretation of the data analysis results and writing the text of the paper

Natalya A. Tikhonova – development of calculation algorithms for harmonic and correlation analysis

Vladimir N. Sukhachev – carrying out calculations and visualization of the results

Ekaterina N. Litina – carrying out calculations and visualization of the results

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.