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Original article

Variance of Short-Period Sea Level Oscillations in the Black Sea: Seasonal and Interannual Variations

I. P. Medvedev

Shirshov Institute of Oceanology of RAS, Moscow, Russian Federation
✉ *patamates@gmail.com*

Abstract
Purpose. The study is aimed at investigating the peculiarities of seasonal and interannual variations of the variance of short-period sea level oscillations in the Black Sea.
Methods and Results. The peculiarities of changes in the variance (energy) of synoptic (2–30 days) and mesoscale (2 h – 2 days) sea level oscillations in the Black Sea were studied based on the analyses of long-term sea level observation series. The results of spectral analysis made it possible to find out that on the eastern coast of the Black Sea, the spectral density of sea level oscillations increases from summer to winter and decreases from winter to summer within the frequency range of 0.1–0.8 cycles/day. As for the northwestern and Crimean coasts, the spectral density is practically the same in autumn and winter, further it decreases in spring and summer. The interannual changes of the variance of synoptic oscillations on the eastern sea coast are characterized by a negative trend achieving – 0.25 cm^2/year in Batumi and – 0.41 cm^2/year in Poti. The variance of mesoscale sea level oscillations has negative trends with the rates from – 0.21…– 0.24 cm^2/year in Odessa and Nikolaev to – 0.13 cm^2/year in Gelendzhik.
Conclusions. The variance of short-period sea level oscillations in the Black Sea increases from summer to winter and decreases from winter to summer that is related to the intensification of cyclonic activity in the atmosphere during autumn and winter. A local seasonal decrease in the variance of sea level oscillations is observed in the estuaries of large rivers in winter due to the developed ice cover preventing the formation of wind surges and seiches. At that, the higher the oscillation frequency, the stronger the ice cover influence.

Keywords: sea level oscillations, Black Sea, synoptic variability, spectrum, variance

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Introduction

The Black Sea is one of the most isolated seas of the World Ocean. Short-period sea level oscillations from adjacent basins (the Mediterranean, Aegean, and Marmara seas) hardly ever pass into the Black Sea due to the narrowness and shallowness of the Bosporus and Dardanelles straits. As a result, short-period oscillations are formed directly inside the sea under the effect of atmospheric processes of a natural synoptic period [1].

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[1] German, V.Kh. and Levikov S.P., 1988. [*Probabilistic Analysis and Modeling of the Sea Level Oscillations*]. Leningrad: Gidrometeoizdat, 231 p. (in Russian).

Tides make the maximum energy contribution, about 85–90%, to the total variance of sea level oscillations in the marginal seas that freely communicate with the open ocean [1]. The tides from adjacent waters also do not penetrate into the Black Sea due to the narrowness of the straits. The sea forms its own tide which is the reaction of the basin water mass to the direct effect of tidal forces [2–4]. The maximum tidal range in the Black Sea varies from 1 cm near the Crimean Peninsula to 18–19 cm in the Dnieper-Bug Estuary and Karkinitsky Bay [3]. The contribution of tides to the total variance of the Black Sea level oscillations varies from 0.3% in Sevastopol to 6% in Batumi [5].

Synoptic (2–30 days) and mesoscale (2 h – 2 days) ranges of the sea level oscillation periods were identified in [5, 6] based on the classification [2]. Synoptic and mesoscale sea level oscillations in the Black Sea are formed mainly under the effect of meteorological factors (atmospheric pressure and wind) [7–9]. In the mesoscale range of periods, dynamic processes are formed under the influence of buoyancy force and the Earth rotation around its axis. The main types of the Black Sea level oscillations in this range of periods are seiches, storm surges, and tides [1, 3, 4] [5, 7, 10]. The effect of buoyancy forces decreases with an increasing period of oscillations in the synoptic variability range and the sea dynamics is determined by the Earth rotation around its axis and the unevenness of this rotation with latitude (β-effect). The main class of motions in this case is planetary Rossby waves [8]. Barotropic waves predominate in the short-period part of the sea synoptic variability, baroclinic waves – in the long-period part and eddy movements (synoptic eddies) – in the interval between them [8].

If in the mesoscale range of the Black Sea level variability one can identify stable peaks related to seiches and tides [10], in the synoptic variability range individual peaks are weakly expressed. A summary table of estimates of oscillation periods in the synoptic and mesoscale ranges obtained by various authors is presented in [8]. A dominant stable peak in the synoptic range is a wide increase in spectral density over periods of 14–16 days characteristic of the steep Crimean and Caucasian coasts [5, 11, 12]. It was demonstrated in [13] that these were coastal trapped Kelvin waves propagating counterclockwise at 2.3–2.6 m/s velocity and having characteristic heights of up to 10–20 cm.

The spectrum evolution of the Black Sea level oscillations with an increase in the frequency of oscillations in various variability ranges from 2 hours to 10 years, as well as variance spatial distribution features of the Black Sea level oscillations in five different frequency ranges were studied in [5] based on long-term series of observations at 23 coastal stations. The synoptic and mesoscale sea level oscillations demonstrate significant unevenness of variance distribution over the water area. The highest values are observed in the shallow northwestern part of the Black Sea. They are due to the surface wind effect. If the variance of seasonal and interannual

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[2] Monin, A., Kamenkovich, V. and Kort, V., 1977. *Variability of the Oceans*. London: John Wiley & Sons Ltd, 241 p.

[3] Blatov, A.S., Bulgakov, N.P., Ivanov, V.A., Kosarev, A.N. and Tuzhilkin, V.S., 1984. *Variability of the Black Sea Hydrophysical Fields*. Leningrad: Gidrometeoizdat, 240 p. (in Russian).

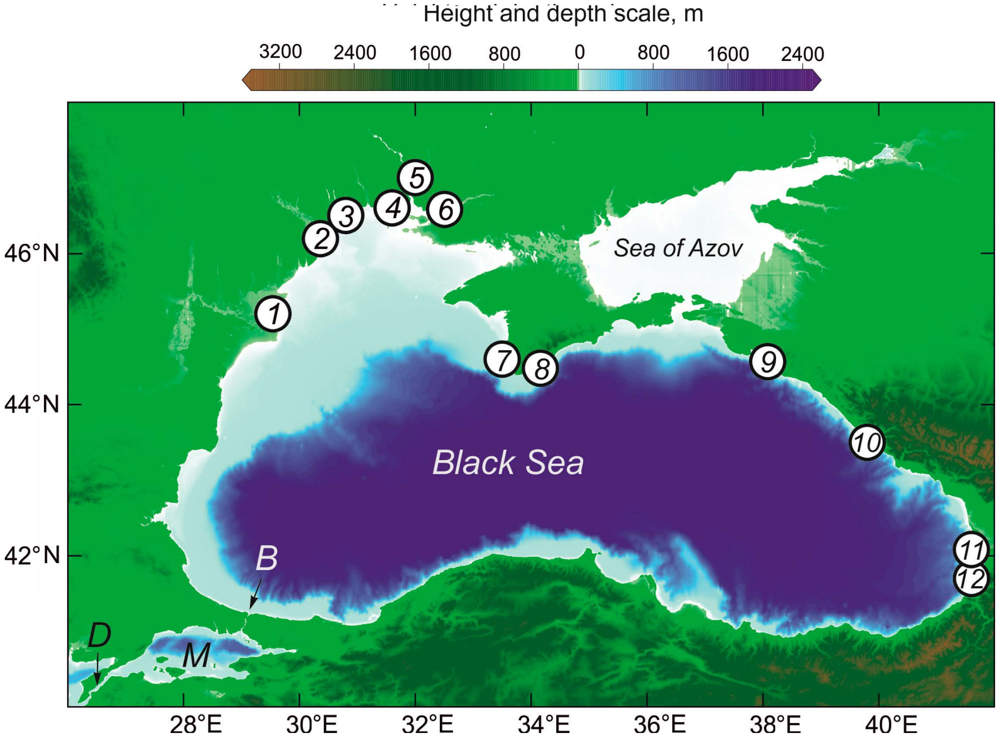
[4] Arkhipkin, V.S., Ivanov, V.A. and Nikolaenko, E.G., 1989. Modeling of Barotropic Seiches in Southern Seas. In: A. S. Sarkisyan, ed., 1989. *Modeling of Hydrophysical Processes and Fields in Closed Basins and Seas*. Moscow: Nauka, pp. 104-117 (in Russian).

sea level oscillations exceeds the variance of synoptic sea level oscillations by approximately 1.5–2 times at stations of the Caucasian coast of the Black Sea (Tuapse, Poti, Batumi) and near the Crimean coast (Sevastopol), then a synoptic component contributes the most to the total sea level variance in the northwestern part. In [11], V.A. Ivanov and V.P. Yastreb assessed the energy characteristics of various types of the Black Sea level oscillations at three points: Poti, Tuapse, and Feodosia based on hourly series. Synoptic variability contribution to the total variance of sea level variations according to [11, 14] is 5–13 times greater than the contribution of mesoscale oscillations.

The above-described studies [5] were continued in this work. The purpose is studying the features of seasonal and interannual variability of the variance of short-period oscillations in the Black Sea level. Qualitative and quantitative estimates of this variability were obtained based on long series of observations.

Materials and methods

Long series of hourly observations of the sea level oscillations at 12 coastal stations from [5] were used for the analysis. Fig. 1 demonstrates the geographical location of the stations in question, which is the post-Soviet coast of the Black Sea (the coast of Russia, Ukraine and Georgia). The data duration varied greatly from station to station, ranging from 3 to 38 years (Table 1).



F i g. 1. Location of the coastal tide gauges whose data were used in the study: *1–12* are station numbers. Other designations: *M* is the Sea of Marmara, *B* is the Bosphorus, *D* is the Dardanelles

Information on the stations in the Black Sea whose observation series were used

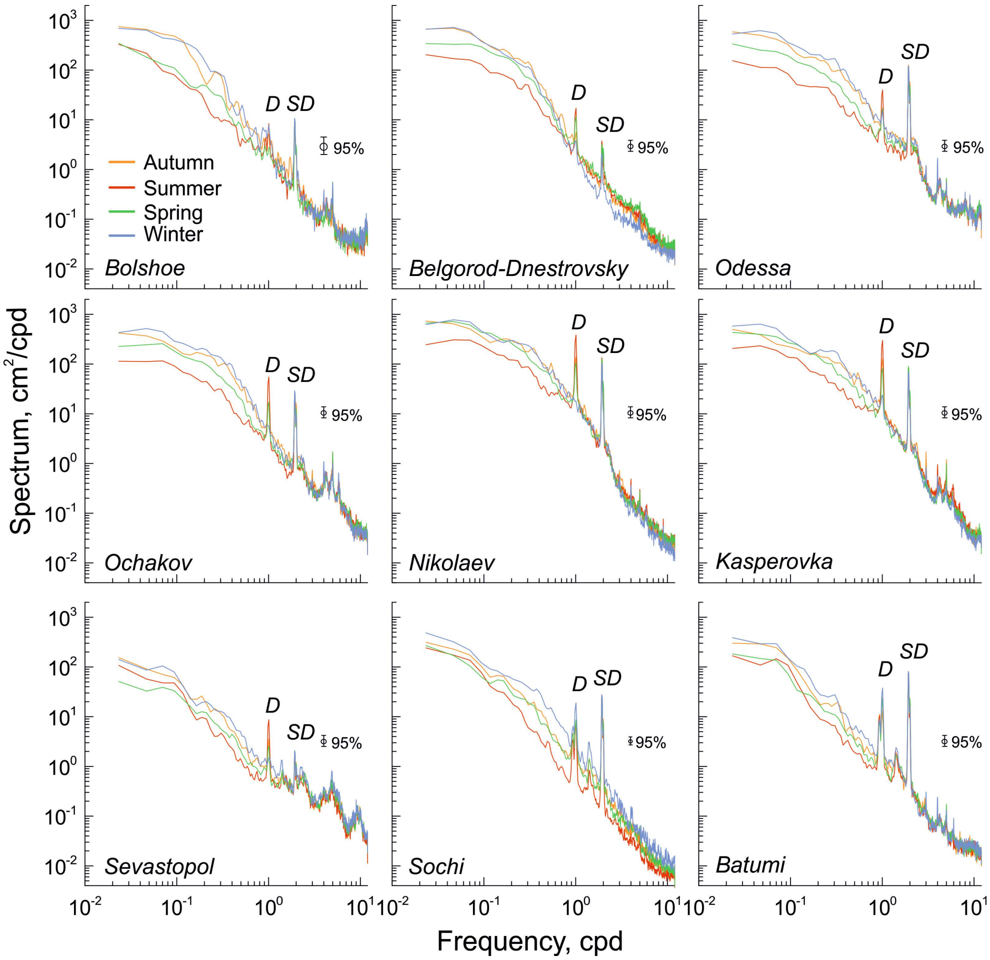
Station No.	Station	Coordinates		Period, years
		°N	°E	
1	Bolshoe	42.5	29.7	1977–1984
2	Belgorod-Dnestrovsky	46.2	30.4	1977–1995
3	Odessa	46.5	30.8	1977–1995
4	Ochakov	46.6	31.6	1977–1995
5	Nikolaev	47.0	32.0	1977–1995
6	Kasperovka	46.6	32.3	1977–1995
7	Sevastopol	44.6	33.5	1977–1995
8	Yalta	44.5	34.2	1977–1995
9	Gelendzhik	44.6	38.1	1977–1992
10	Sochi	43.5	39.8	1977–2014
11	Poti	42.1	41.6	1977–1991
12	Batumi	41.7	41.6	1977–1991

Results and discussion

Seasonal variations in the spectrum of Black Sea level oscillations

The spectral density of sea level oscillations steadily decreases with increasing frequency f of oscillations according to the law f^{-2}, i.e., it corresponds to “red noise” (Fig. 2). Disturbances in the continuous decay of the spectrum are caused primarily by two main factors: 1) tidal components and 2) frequency-selective properties of the basin. Tides manifest themselves as sharp spectral peaks at fixed diurnal and semidiurnal frequencies (*D* and *SD* in Fig. 2). Sea level variations caused by variable air pressure and wind are mainly in the nature of random noise and have a spectrum in the form of a continuous function of frequency (continuum). The nature of the continuous part of the spectrum changes depending on the frequency-selective properties of the entire sea and the water area of its individual parts (gulfs and bays). Local “humps” of a continuous spectrum are formed near the resonant frequencies, where the energy of natural oscillations of the basin level (seiches) is concentrated.

The nature of seasonal variability of the spectra varies greatly depending on the frequency. In the low-frequency range (< 0.8 cycle/day), a significant difference in the energy of the winter and summer spectra is observed. The eastern coast of the sea (Batumi and Sochi) is characterized by an increase in spectral density from summer to winter and a decrease from winter to summer. Moreover, in autumn and spring seasons the spectra have a similar energy level. For the northwestern (Ochakov, Odessa, and Bolshoe) and Crimean coasts, the spectral density in autumn and winter is almost the same further decreasing in spring and summer. At the stations Nikolaev, Kasperovka, and Belgorod-Dnestrovsky, located in the estuaries of large rivers (the Southern Bug, Dnieper, and Dniester, respectively), the spectral density in winter, autumn and spring has similar values. The increase in spectral density in the autumn-winter period is associated with the intensification of cyclonic activity in the atmosphere. Such winter intensification is not observed in the estuaries of large rivers apparently due to the ice cover, which partially dampens synoptic oscillations of sea level.



F i g. 2. Seasonal spectra of the sea level oscillations at nine stations in the Black Sea

In the high-frequency region of the spectrum (> 1.2 cycle/day), the level of spectral density varies slightly depending on the season at almost all the stations under consideration. The exception is the spectra for the Sochi, where seasonal variability of high-frequency oscillations repeats the feature characteristic of the low-frequency spectrum region of this station – intensification in winter. At stations located in the estuaries of large rivers (Nikolaev, Kasperovka and Belgorod-Dnestrovsky), the energy of high-frequency sea level oscillations in winter is even slightly inferior to the spectral density characteristic of other seasons of the year. This is probably due to the development of ice cover in the winter season [15] which prevents formation of the sea level oscillations of wind origin (surges and seiches) in the estuaries.

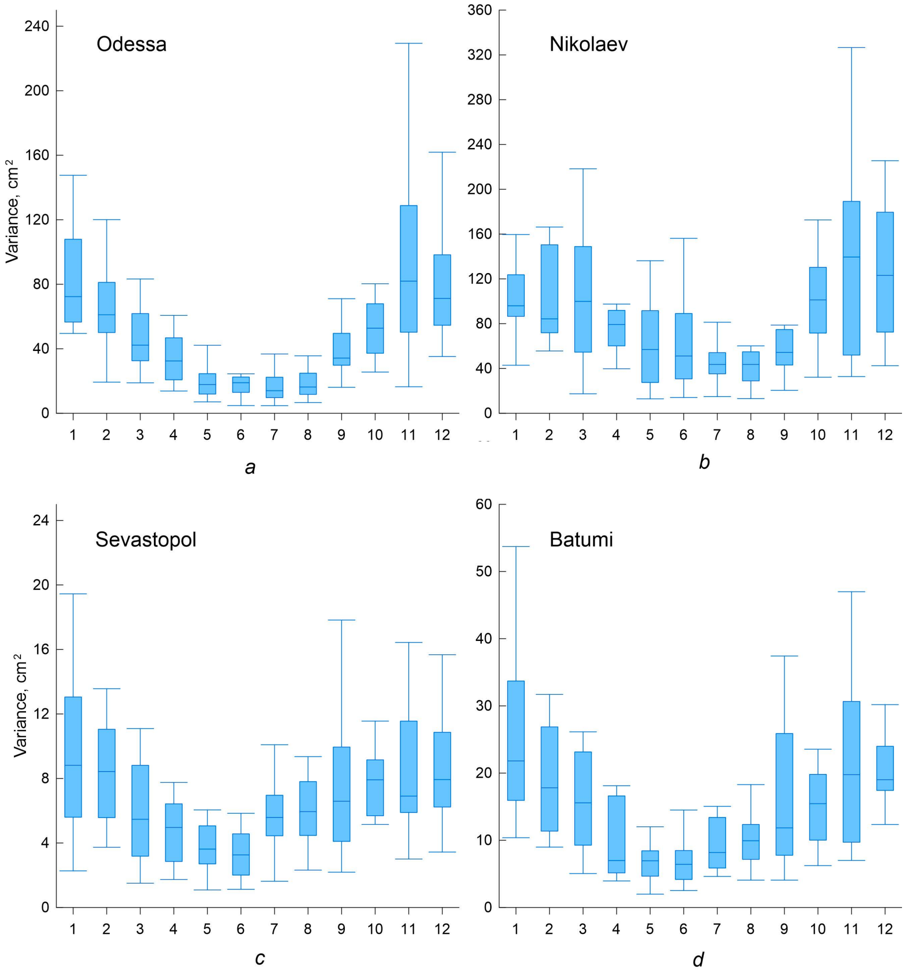
In Fig. 2, special attention should be paid to radiational (thermal) tidal spectral peaks at frequencies of 1 cycle/day and multiple frequencies. Radiational tides are movements of water directly or indirectly associated with solar radiation [3, 10]. They are formed under the combined effect of various periodic factors: diurnal oscillations of water and air temperatures, atmospheric tides, and breeze winds. The detailed information about the features of radiational and gravitational tides in the Black Sea is given in [3].

The diurnal peaks in Fig. 2 apparently have a significant contribution from the radiation component. As a result, the peak with a frequency of 1 cycle/day varies greatly throughout the year: in winter it is the weakest and at some stations (Ochakov, Nikolaev, Sevastopol) it is even absent. In summer, this peak reaches maximum energy values even exceeding the semi-diurnal tidal peak at Ochakov, Nikolaev, and Kasperovka. It should be noted that seasonal variability of the diurnal peak at most stations is in antiphase to the nature of the seasonal variability of the spectrum continuous part in the frequency range of 0.2–2 cycle/day.

These features of spectrum seasonal variability confirm the hypothesis about the breeze origin of these diurnal spectral peaks [3, 10]. On the northern coast of the Black Sea, breeze winds are observed from April to October [16]. The highest frequency of breezes is observed on the southern coast of Crimea – on average more than 50 days/year, in some places up to 190 days/year (Yalta) [16]. At the Caucasian coast, the frequency of breezes increases from north to south from 18 to 50 days/year [16]. According to [17], the energy of diurnal sea level oscillations off the coast of Bulgaria in summer is 3–4 times greater than in winter. In [18] it was demonstrated that the breeze wind off the coast of Bulgaria causes diurnal sea level oscillations of about 3–4 cm amplitude, while the influence of water temperature diurnal variations on the sea level variation is negligible. The semi-diurnal spectral peak in Fig. 2 has an astronomical tidal origin [3], as a result of which it does not undergo any special variations from season to season.

Seasonal changes in the variance of synoptic level oscillations

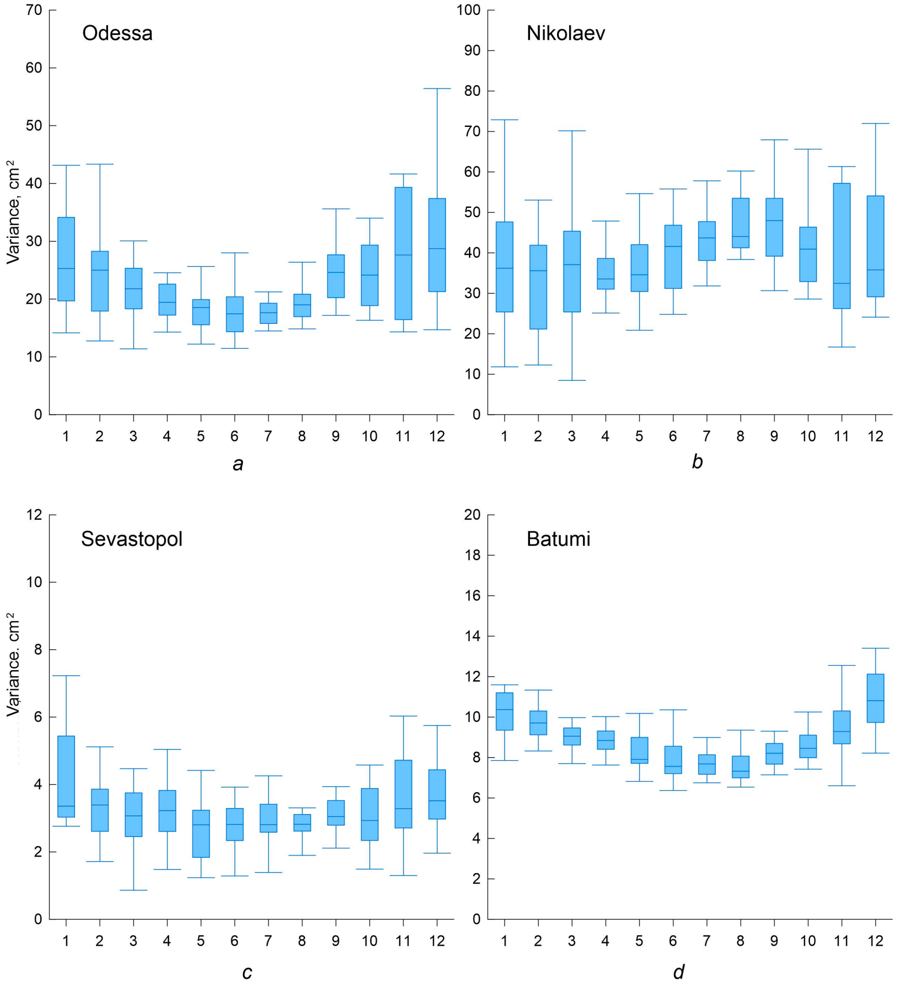
To quantify the seasonal variability of energy of short-period sea level oscillations in the Black Sea, we calculated the spectra for each monthly series of hourly observations and variance values were obtained in various frequency ranges. Residual (non-tidal) series of sea level variations were applied for calculations. They were obtained by subtracting from the original series the sea level variations of tidal oscillations, calculated using harmonic analysis by the least squares method [3]. The main attention was paid to the synoptic range with oscillation periods from 2 days to one month, as well as the mesoscale range with oscillation periods from 2 hours to 2 days. The variance for the selected ranges can be estimated as $\sigma^2 = \Delta f \sum S(f_i)$, where Δf is spectral frequency resolution, and i varies within specified limits. Next, the median, lower (first) and upper (third) quartiles (25th and 75th percentiles, respectively) were calculated for each month. The edges of a statistically significant sample (the ends of the whiskers) were determined by the difference between the first quartile and one and a half interquartile distances (in the case of the lower one) and the sum of the third quartile and one and a half interquartile distances (in the case of the upper one). The interquartile distance (interquartile range, IQR) is defined as the difference between the values of the third and the first quartiles.



F i g. 3. Box plots of seasonal variations of the variance of synoptic sea level oscillations at the stations Odessa (*a*), Nikolaev (*b*), Sevastopol (*c*), and Batumi (*d*)

In Fig. 3 the calculated box plots ("boxes with whiskers") of variance estimates of synoptic sea level oscillations for Odessa, Nikolaev, Sevastopol, and Batumi stations are given. All four stations are characterized by high variance values in the autumn-winter period and lower ones in the summer. Moreover, in the deep-water parts of the sea (Sevastopol and Batumi) the minimum variance is observed from May to June, in Odessa this period is wider – from May to August and in Nikolaev it shifts towards the end of summer – from July to August. The interannual spread of variance estimates from November to January is also significantly higher than in other months. In the northwestern part of the sea (Fig. 3, *a*, *b*), the maximum median value of the variance, as well as the spread of extreme values, reaches its maximum in November. In Nikolaev, the river runoff influence, which increases the spread of variance estimates in May – June, is likely to be felt. In Sevastopol and Batumi, the maximum median values are observed in January (Fig. 3, *c*, *d*).

In September, these stations demonstrate local increase in both the median estimate and the spread.



F i g. 4. Box plots of seasonal variations of the variance of mesoscale sea level oscillations at the stations Odessa (*a*), Nikolaev (*b*), Sevastopol (*c*), and Batumi (*d*)

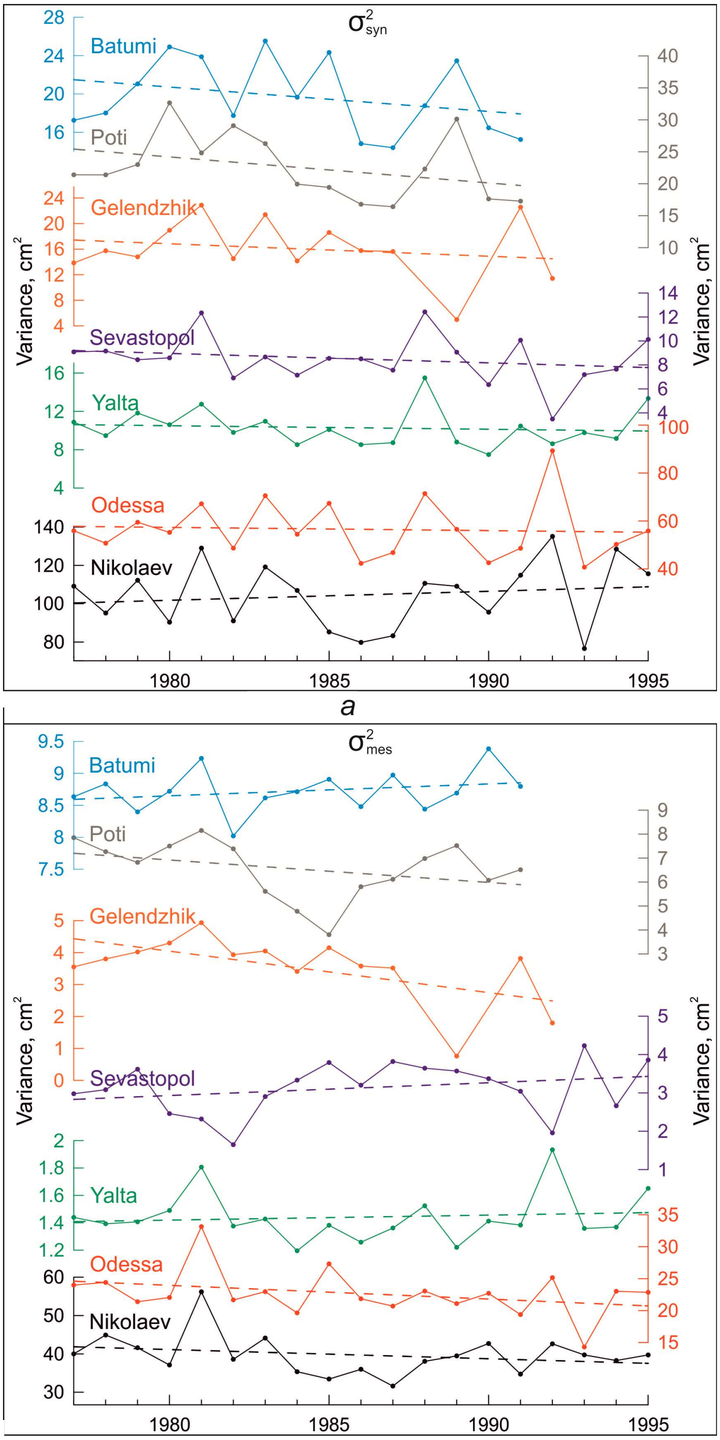
The mesoscale variability range is characterized by different box plots of variance estimates of sea level oscillations (Fig. 4). The maximum values are observed in autumn and winter. The minimum values of the median variance in Odessa, Sevastopol, and Batumi are typical for May – August. In Nikolaev, the lowest variance values are observed in April, May, and November. The spread of variance values at three stations (Fig. 4, *a*, *c*, *d*) decreases from winter to summer and increases from summer to winter. Nikolaev is characterized by atypical histograms with an increase in median variance values from May to September followed by a decrease in the median and an increase in variance by November – December.

The cause of this effect is probably the interannual variability of the ice cover. In years with maximum duration of the ice cover, the variance values of mesoscale sea level oscillations are lower compared to the summer months. For example, this is illustrated by the lower whiskers from November to March in the diagrams in Nikolaev (Fig. 3, *b*). Due to the fact that prolonged ice cover in the Bug Estuary is observed almost every year [15], the median variance values in November – December are also lower than in other months. Winters with weak ice cover are characterized by an increase in the variance of mesoscale oscillations caused by cyclonic activity, as evidenced by the maximum values of the diagrams for the winter months (upper whiskers).

Interannual variations in the variance of short-period level oscillations

As was shown in the previous section, variance estimates for individual months vary from year to year. To analyze the interannual variability of the variance of short-period sea level oscillations, average annual values were calculated. Fig. 5 demonstrates the annual variance of synoptic (*a*) and mesoscale (*b*) sea level oscillations. The coefficient of variation (c_v), reflecting the variability degree of σ^2_{syn} values in relation to the average sample value, ranged from 0.17 for the Nikolaev to 0.29 for the Gelendzhik. Interannual variations in σ^2_{syn} on the eastern coast of the sea are characterized by a negative trend of up to -0.25 cm^2/year in Batumi and -0.41 cm^2/year in Poti, which is proportional to σ^2_{syn} decrease by 1.3 and 1.8% per year from the average value, respectively (Fig. 5, *a*). For the Crimean and northwestern coasts of the sea there isn’t a clearly defined trend, but in Nikolaev there is already a weak trend towards an increase in σ^2_{syn} from 1977 to 1995 at a rate of 0.46 cm^2/year (0.44%).

The variance values of mesoscale oscillations σ^2_{mes} at some stations also vary significantly from year to year (Fig. 5, *b*). The coefficient of variation for Sevastopol, Gelendzhik, and Poti is 0.22, 0.30 and 0.18, respectively. For Yalta, Odessa, Nikolaev c_v decreases to 0.13–0.16. In Batumi c_v is 0.04, which reflects weak interannual variability of σ^2_{mes} values. Thus, two nearby stations (Batumi and Poti) have different patterns of interannual σ^2_{mes} variations (Fig. 5, *b*). Moreover, if in Batumi no significant trends in σ^2_{mes} variations were identified, in Poti a negative trend at a rate of -0.09 cm^2/year (1.4%) was observed. In Gelendzhik, the nature of interannual variations is different, but the rate of σ^2_{mes} decrease is even higher than in Poti (-0.13 cm^2/year (3.7%)). For the Crimean coast, pronounced trends in interannual variability are absent. Moreover, in Sevastopol and Yalta σ^2_{mes} interannual variations occur in antiphase. In Odessa and Nikolaev, we observed a similar pattern of interannual variability with a weak negative trend ($-0.21...-0.24$ cm^2/year; 0.6–0.9%) in σ^2_{mes} values.



a

b

F i g. 5. Interannual changes of variance of the synoptic (*a*) and mesoscale (*b*) Black Sea level oscillations at the stations Batumi, Poti, Gelendzhik, Sevastopol, Yalta, Odessa, and Nikolaev. The dashed line shows long-term linear trends

Conclusions

The long-term series of sea level observations made it possible to study the features of variance (energy) changes of the Black Sea level oscillations. Based on the results of spectral analysis, this work provided quantitative and qualitative characteristics of seasonal and interannual sea level variability in various physical and geographical conditions.

On the eastern coast of the Black Sea, the spectral density of sea level oscillations increases from summer to winter and decreases from winter to summer within the frequency range of 0.1–0.8 cycle/day. For the northwestern (Ochakov, Odessa, and Bolshoe) and Crimean coasts, the spectral density level in autumn and winter is almost the same, further decreasing in spring and summer. These features of seasonal variability in the spectrum of sea level oscillations are associated with the intensification of cyclonic activity in the atmosphere in the autumn-winter period.

In the estuaries of large rivers (for example, Nikolaev, Kasperovka, and Belgorod-Dnestrovsky stations), developed ice cover in winter prevents the formation of wind-induced oscillations in sea level (surges and seiches) due to which spectral energy decreases. Moreover, the higher the frequency, the more important the role played by the ice cover. Thus, in the synoptic frequency range in these sea areas, the spectral density level in winter is close to the autumn and spring values and in the mesoscale frequency range it is even lower.

The pronounced diurnal spectral peak is of radiational (thermal) tidal origin, in contrast to the semi-diurnal peak associated with classical astronomical tides. Apparently, the main factor affecting the formation of this peak is breeze winds. As a result, the diurnal peak is weakly distinguished in the winter season and reaches its maximum energy values in summer when the breeze circulation is most developed.

The variance values of sea level oscillations vary both from month to month and from year to year. To analyze the interannual variability of the variance of short-period sea level oscillations, average annual values were calculated. Interannual changes in the variance of synoptic oscillations on the eastern coast of the sea are characterized by a negative trend of up to -0.25 cm^2/year in Batumi and -0.41 cm^2/year in Poti, which is 1.3 and 1.8% of the average value, respectively. The variance of mesoscale sea level oscillations has negative trends with rates from $-0.21...-0.24$ cm^2/year (0.6–0.9%) in Odessa and Nikolaev to -0.13 cm^2/year (3.7%) in Gelendzhik.

Based on the obtained results, the seasonal and interannual variability of energy of the Black Sea level oscillations was assessed. In the case of a mesoscale range of periods, these estimates reflect the variability of sea level oscillations of wind origin, primarily surge phenomena and seiches.

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About the author:

Igor P. Medvedev, Leading Research Associate, Tsunami Laboratory, Shirshov Institute of Oceanology of RAS (36 Nakhimovsky ave, Moscow, 117997, Russian Federation), CSc (Phys.-Math.), **ORCID ID: 0000-0003-0748-0062**, **Scopus Author ID: 55656381400**, **Researcher ID: L-6118-2013**, patamates@gmail.com

The author has read and approved the final manuscript.
The author declares that he has no conflict of interest.