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Original article

Climatic Spectra of Surface Elevation Fluctuations in the Sea of Azov

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Abstract
Purpose. The article is purposed at studying climatic fluctuations of the Azov Sea level on the scales of mesoscale and synoptic variability.
Methods and Results. Hourly sea level rises in 1979–2020 obtained by the methods of numerical modeling using the coupled hydrodynamic (ADCIRC) and wave (MIKE 21 SW) models constitute the initial data for the analysis. The basic harmonics of sea level oscillations in the ranges of mesoscale and synoptic variability were determined, and spatial and seasonal characteristics of the oscillations were assessed.
Conclusions. Main sea level oscillations in the ranges of synoptic and mesoscale variability are concentrated in the following periods (within a day): 0.5; 1; 1.8–2.5; 3–5; 5.5–7; 8.5–11; 12.5–13.5; 14.5–17. Sea level fluctuations with the periods exceeding two days have a form of a uninodal seiche whose amplitude maxima are in the coastal zone of two opposite areas: in the southwest of the sea (along the Arabat Spit) and in the northeast region (from the Yasenskaya to the Belosarayskaya spits). The seiche central line runs conventionally from the Temryuk Bay through the sea center to the bay between the Obitochnaya and the Berdyansk spits. In the case of semi-diurnal variations, the central line of fluctuations runs from the middle of the Arabat Spit through the sea center to the Dolgaya Spit. The level fluctuations with the periods exceeding two days are observed mainly in spring and autumn, namely from March to April and from September to November. Diurnal variations are virtually independent of the season. Semi-diurnal harmonics are most pronounced in spring and autumn, and weaken considerably in the summer months. The sea level fluctuations and the zonal component of wind speed have high coherence coefficients over the entire range of frequency-time variability. The relationship between sea level fluctuations and the meridional component of wind speed is manifested mainly in the diurnal and semidiurnal cycles.

Keywords: numerical modeling, Sea of Azov, level fluctuations, spectra, climatic variability

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Introduction

The principal factors determining the Sea of Azov level regime are direct wind influence, atmospheric pressure fluctuations, wind waves, wave and storm surges, river runoff, and tidal movements. In addition, sea level is influenced by local morphodynamic and bathymetric features, and also depends on the water area ice cover in winter.

To date, the most studied are free (seiche) oscillations of the basin level, i.e. oscillations in the range of periods from several to tens of hours [1–6]. In the monograph [1], based on the analysis of instrumental observations at twelve points along the Sea of Azov perimeter, the first three modes of level fluctuations with periods of about 24, 15 and 12.5 hours are determined. In the Yu.V. Manilyuk's thesis [2], entirely devoted to the seiche and surge phenomena of the Sea of Azov, the periods of its natural oscillations were 27.9; 16.3 and 12.5 hours. Other periods of the first oscillation modes, amounting to 38.4; 23.7 and 12.1 hours are given in articles [7, 8]. An interesting view on the nature of daily and semi-diurnal level fluctuations was proposed in [9, 10], which analyzed the contribution to level fluctuations of gravitational and radiation (thermal) tides and concluded that gravity tides predominated in the northern part of the sea, and mixed and gravitational-radiation tides in the southern.

In any case, as studies have shown, the nature of fluctuations in the level of the shallow and relatively small-sized Sea of Azov is complex. The hydrodynamic factors that determine level fluctuations are highly interrelated.

These circumstances define the objectives of the present work:

1) construction of climatic spectra of level elevation fluctuations and analysis of the spectral structure in the ranges of meso- and synoptic variability,

2) assessment of spatial features of level fluctuations in the Sea of Azov waters,

3) study of intra-annual (seasonal) variability of fluctuations.

The main research method is numerical modeling.

Materials and methods

The research results presented in the introduction were based, as a rule, on the consideration of certain artificial situations (stationary wind, cyclone passage over the water area, etc.), justified from the viewpoint of setting a specific problem, but still somewhat simplified. The present paper is mainly aimed at analyzing the climatic spectra of level elevations, formed under the influence of a large number of various interrelated factors, in other words, to obtain a real climatic picture of level fluctuations.

In the absence of sufficiently long-term, continuous, geographically dispersed data with acceptable time discreteness of direct field observations of sea level, perhaps numerical modeling is the only means of research. This method makes it possible to correctly take into account all the main mechanisms of interaction between atmospheric conditions, current systems, surface waves, wave and storm surges.

At our disposal, we have the fields of the main hydrodynamic Sea of Azov parameters calculated over 42 years (from 1979 to 2020), obtained using a combined three-dimensional hydrodynamic and spectral wave models [11].

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

[2] Manilyuk, Yu.V., 2021. [*Seiche and Surge Fluctuations in the Black and Azov Seas*]. Thesis Cand. Phys.-Math. Sci. Sevastopol, 168 p. (in Russian).

Below a brief discussion of the main approaches used in modeling the Sea of Azov water dynamics is given:

1. Selection of the required atmospheric forcing fields (surface pressure, wind speed components), as well as sea ice concentration, is made from the publicly available ERA5 database provided by the European Center for Medium-Range Forecasts (ECMWF). Calculation area: 34.75°–39.50°E, 45.25°– 47.50°N. Spatial steps in latitude and longitude are 0.125°; in time – 3 hours for atmospheric pressure and wind fields, one day – for ice concentration. The calculation grid (Fig. 1) is based on a modern bathymetric map of the Sea of Azov [12].

F i g. 1. Bathymetric map, morphometric features of the Sea of Azov, and location of the experimental and calculated stations for analyzing the level

2. Wind wave parameters are calculated using the MIKE 21 SW spectral wave model. A thorough verification of the model was carried out for the conditions of the Black and Azov Seas [13]. Based on the 5-layer σ-coordinate (vertical) three-dimensional hydrodynamic ADCIRC model, fields of parameters of sea currents and level elevations were obtained. This model has shown its effectiveness in studying extreme storm surges in the Sea of Azov [14]. Combining hydrodynamic and wave models into a single calculation block permits to take into account the most important aspects of the interaction of currents and surface waves.

Since the paper is aimed at studying climatic variability in sea level, the combined model must be verified using sufficiently long-term experimental data. Here certain difficulties are encountered. Firstly, despite a rather dense network of observations of the Sea of Azov level, the data has a number of shortcomings, for example, there are gaps in the data that exclude the possibility of correct interpolation, different frequencies of measurements, and unequal and not always perfect instrumentation. Secondly, the ice maps available in the ERA5 reanalysis can (with an inevitable probability) differ from the actual observed ones, which entails errors in sea level calculations. Accordingly, for further analysis, samples consisting of hourly level marks for nine ice-free months (March–November) of each of the eight years of observations in the following points: Genichesk, Mariupol, Opasnoe (1997–2004), Temryuk (1980, 1982–1986, 1988, 1989) were formed. For comparison with experimental data for the same periods, calculated series of level elevations, also with discreteness of 1 hour, were formed.

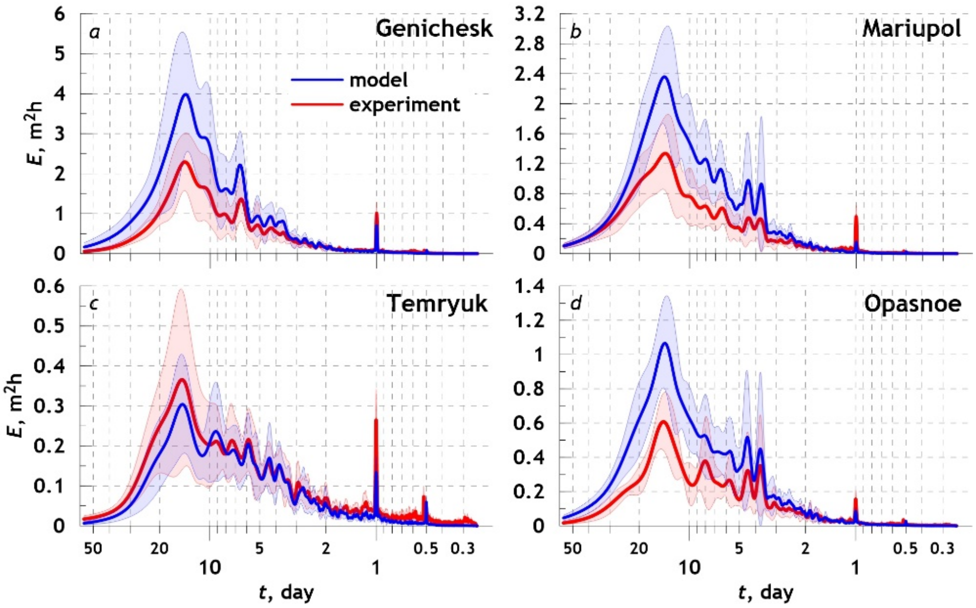
The climatic variability analysis was carried out based on calculated data for the entire period available, from 1979 to 2020, at 29 points covering the main Sea of Azov water area (Fig. 1). Since winter months are not considered, interannual variability is excluded from the analysis. The necessary calculations were carried out in Matlab using Welch's periodogram method.

Results and discussion

Fig. 2 shows the experimental and calculated spectra of level fluctuations averaged over eight years in Genichesk, Mariupol, Temryuk, and Opasnoe. The shaded areas in Fig. 2 correspond to 95% confidence intervals.

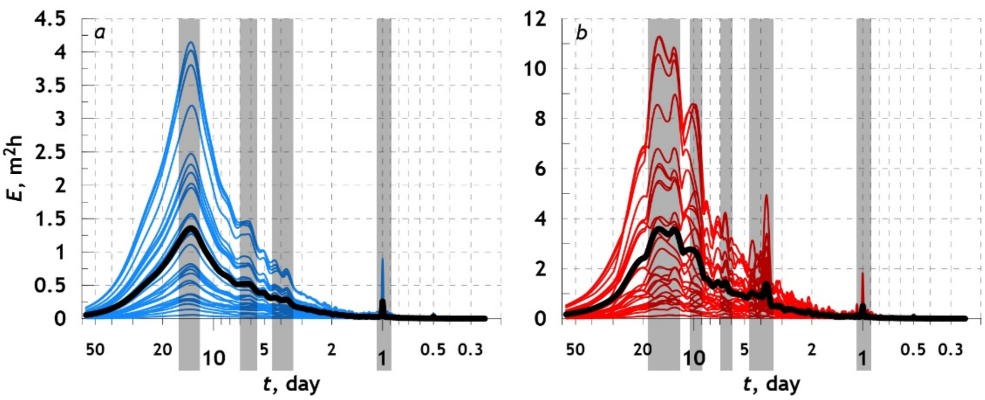
As follows from Fig. 2, the level fluctuations present in both experimental and model series of free surface elevation are almost synchronous. The model reproduces the main spectral peaks correctly during periods of synoptic and mesoscale oscillations. A slight difference is visible in the oscillation amplitudes. The energy of synoptic oscillations with periods exceeding 2–3 days is slightly greater for the model series than for the experimental ones. The opposite picture is observed in the range of oscillations with the periods of 12–48 hours, which is quite possibly stipulated by a rather coarse spatial and temporal resolution of the original wind fields represented by the ERA5 reanalysis. Global reanalysis does not sufficiently take into account local small-scale atmospheric features, particularly, those occurring at the sea-land interface. It also should be noted that considering experimental data as a kind of standard is, in fact, a forced measure. Despite the relative simplicity of design, tide gauges used at hydrometeorological stations require mandatory and careful maintenance. We don't question in any way the personnel qualifications, but we remind you that one should not forget about possible objective sources of errors (wear and play of mechanisms, condition of wells, etc.). Thus, based on Fig. 2, it is concluded that the hydrodynamic model quite correctly reproduces the main patterns of the Sea of Azov level formation and can serve as a tool for further research.

For each of the 29 selected points (Fig. 1), 42 spectra, characterizing level fluctuations for the March–November period of each year from 1979 to 2020 were obtained. Statistical processing of these spectra allows constructing mean and maximum climatic spectra of fluctuations. Fig. 3 shows the mean (Fig. 3, *a*) and maximum (Fig. 3, *b*) spectra calculated for all 29 points.



F i g. 2. Mean annual experimental (red lines) and model (blue lines) spectra of level fluctuations over the ice-free period in the selected points of the Azov Sea

The mean spectra (Fig. 3, *a*) are highly smoothed and demonstrate, in fact, two principal features: dominant oscillations in the range of 12–16-day periods with a main peak around 13.5 days, as well as stable daily oscillations and fluctuations with periods of 5.5–7.0 and 3.5–4.5 days. These harmonics, but with their own characteristics, are much more pronounced in the maximum spectra (Fig. 3, *b*). The main oscillation energy is concentrated in the interval of 12.4–18.3 and 8.9–10.4 days. Peaks in the ranges of 6–7 and 3.4–4.7 days, as well as the daily cycle, are clearly distinguishable. The semidiurnal harmonic, which is extremely weak in absolute terms, nevertheless is manifested in both mean and maximum spectra.



F i g. 3. Mean (*a*) and maximum (*b*) spectra of sea level fluctuations for the period from 1979 to 2020 at 29 points in the sea area

Black lines in Fig. 3, corresponding to the spectra averaged over all 29 points, indicate that the noted periods of oscillations are specific for the entire sea area. We are to find out whether there are spatial features in the formation of level oscillation spectra. The maximum spectra analysis at neighbouring points made it possible to identify the Sea of Azov coast sections with similar spectral structures of oscillations.

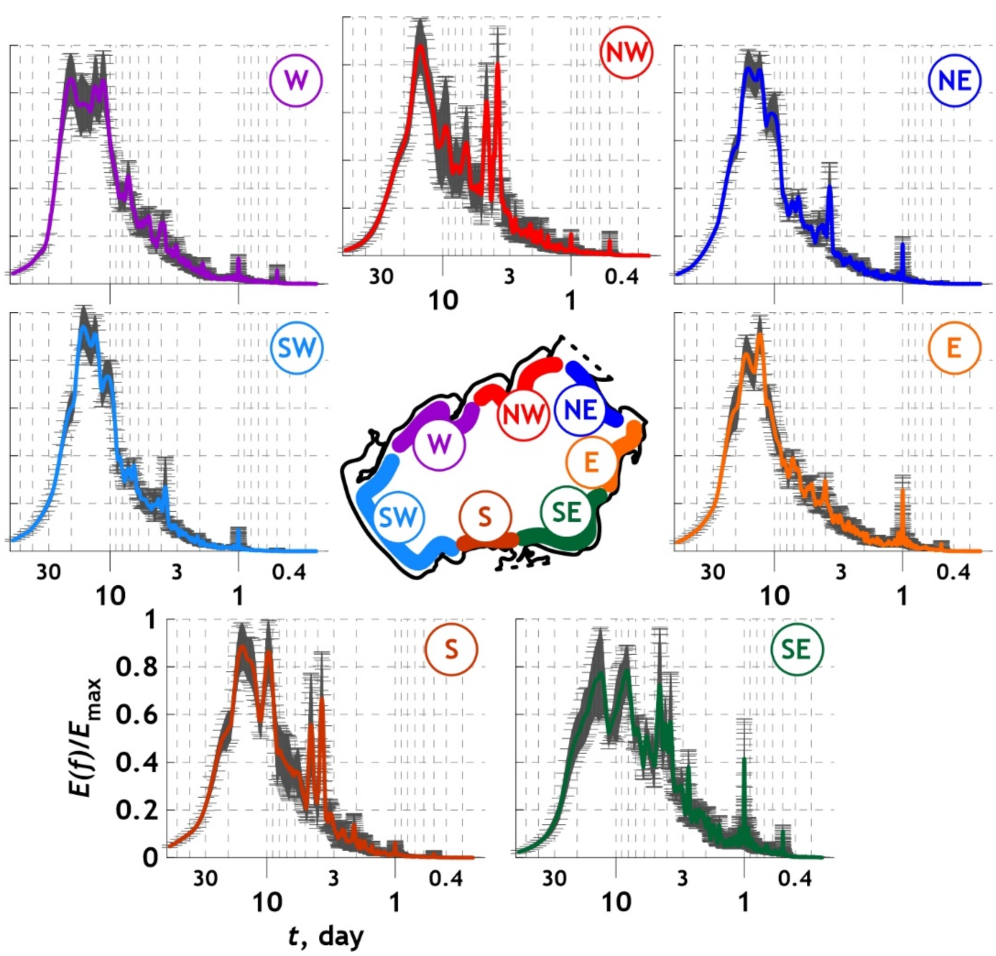
Fig. 4 shows the averaged maximum spectra and their 95% confidence intervals, characterizing patterns in level fluctuations in the ranges of synoptic and mesoscale variability of the coastal sea zone. The spectra are normalized as it is more convenient to estimate the ratio of oscillation amplitudes at different frequencies. It is also noted that the accepted names of the sites are, naturally, somewhat arbitrary. Fig. 5 shows in illustrative form the main periods corresponding to the peaks of spectral densities in Fig. 4.

As follows from Fig. 4 and 5, the main fluctuations in sea level in the ranges of synoptic and mesoscale variability are concentrated in the following periods (in days): 0.5; 1; 1.8–2.5; 3–5; 5.5–7; 8.5–11; 12.5–13.5; 14.5–17. Semi-diurnal fluctuations are the smallest in amplitude, and at the same time they are almost imperceptible only in two opposite areas: in the southwest and northeast of the sea. Two-day fluctuations are quite weak throughout the entire sea area. Strong daily fluctuations, comparable in power to other peaks, are observed in the southeast of the sea, with a cyclicity of 3–5 days in the northwest, southeast and south. Throughout the entire coastal zone of the sea, fluctuations are well pronounced at periods of 5.5–7 and 8.5–11 days. Steady fluctuations with periods of 12.5–13.5 days are observed almost everywhere except in the northwest. Fluctuations with periods exceeding 15 days, concentrated mainly in the range of 15–17 days, are characteristic of the entire sea, excluding the southeast. At the same time, the longest periods of fluctuations (almost 20 days) are found in the west of the sea.

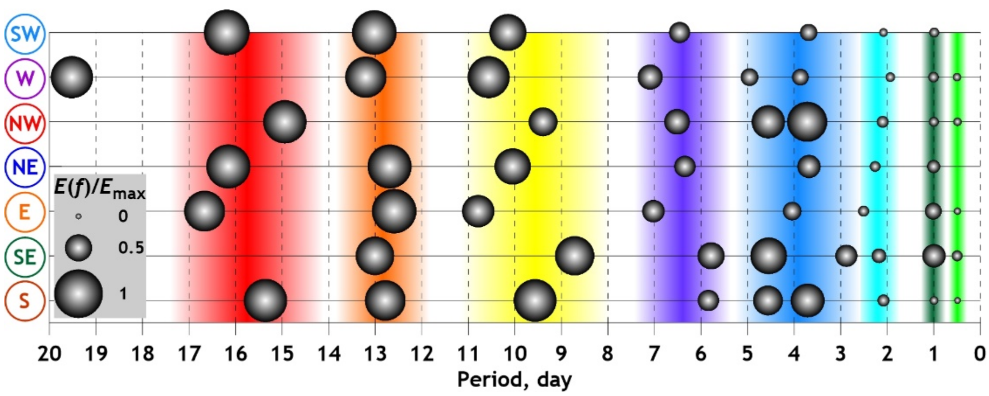
An important detail should be noted. Statements about the complete absence of fluctuations at certain frequencies are hardly appropriate. It is about the presence (or absence) of obvious peaks in the averaged (climatic) spectra.

The spatial structure of climatic fluctuations in the Sea of Azov level is presented in Fig. 6. The maximum values of spectral densities are shown here by range of temporal variability (in days): over 14.5; 12.5–13.5; 8.5–11; 5.5–7; 3–5; 1.8–2.5; 1; 0.5.

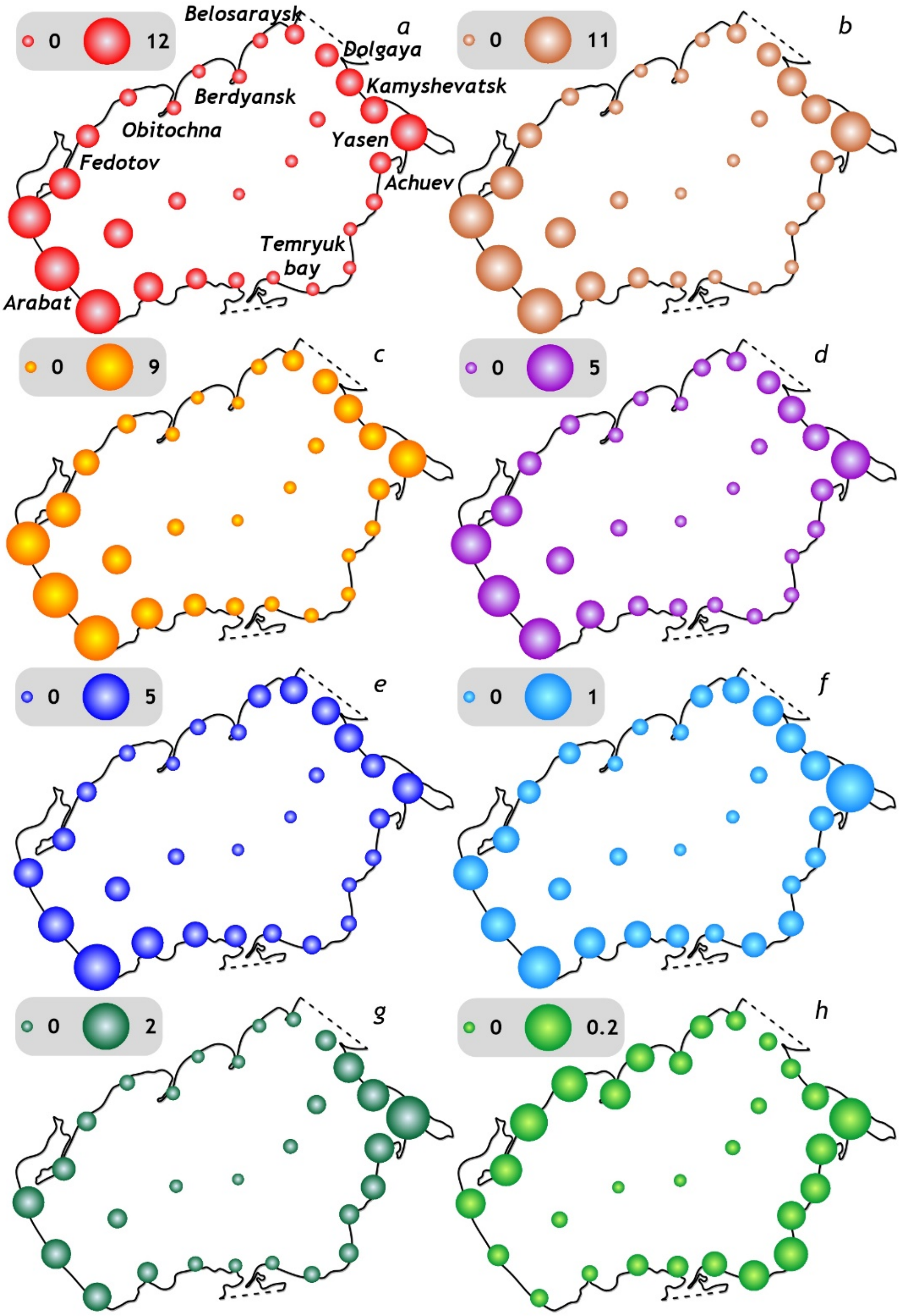
The strongest in the general structure of synoptic and mesoscale variability are fluctuations with periods exceeding 14.5 days (Fig. 6, *a*). In general, comparable to them are fluctuations of somewhat smaller amplitude with periods of 12.5–13.5 (Fig. 6, *b*) and 8.5–11 (Fig. 6, *c*) days. The fluctuation powers for periods of 5.5–7 (Fig. 6, *d*) and 3–5 (Fig. 6, *e*) days are almost the same. Fluctuation cycles with periods of 1.8–2.5 days (Fig. 6, *f*) are half as long as daily ones (Fig. 6, *g*). The weakest are the semi-diurnal fluctuations (Fig. 6, *h*), which are an order of magnitude smaller than the diurnal ones.



F i g. 4. Spatial features of the climatic maximum spectra of sea level fluctuations



F i g. 5. Main periods of sea level fluctuations in the Sea of Azov coastal zone



F i g. 6. Maximum spectral densities ($m^2 \cdot h$) for the fluctuation periods (day): *a* – 14.5–17; *b* – 12.5–13.5; *c* – 8.5–11; *d* – 5.5–7; *e* – 3–5; *f* – 1.8–2.5; *g* – 1; *h* – 0.5

As follows from Fig. 6, in spatial terms, level fluctuations with periods of over two days actually have the form of a single-node seiche with amplitude maxima in the coastal zone of two opposite areas: in the southwest of the sea, along the Arabatskaya Spit, and in the northeast, from the Yasenskaya Spit to the Belosarayskaya Spit. The seiche center runs from the Temryuk Bay through the sea center to the bay between the Obitochnaya and Berdyanskaya spits. At the same time, the fluctuations in the southwest are generally more powerful than the fluctuations in the northeast, excluding the range of periods of 1.8–2.5 days with a clear maximum in the Yasenskaya Spit area.

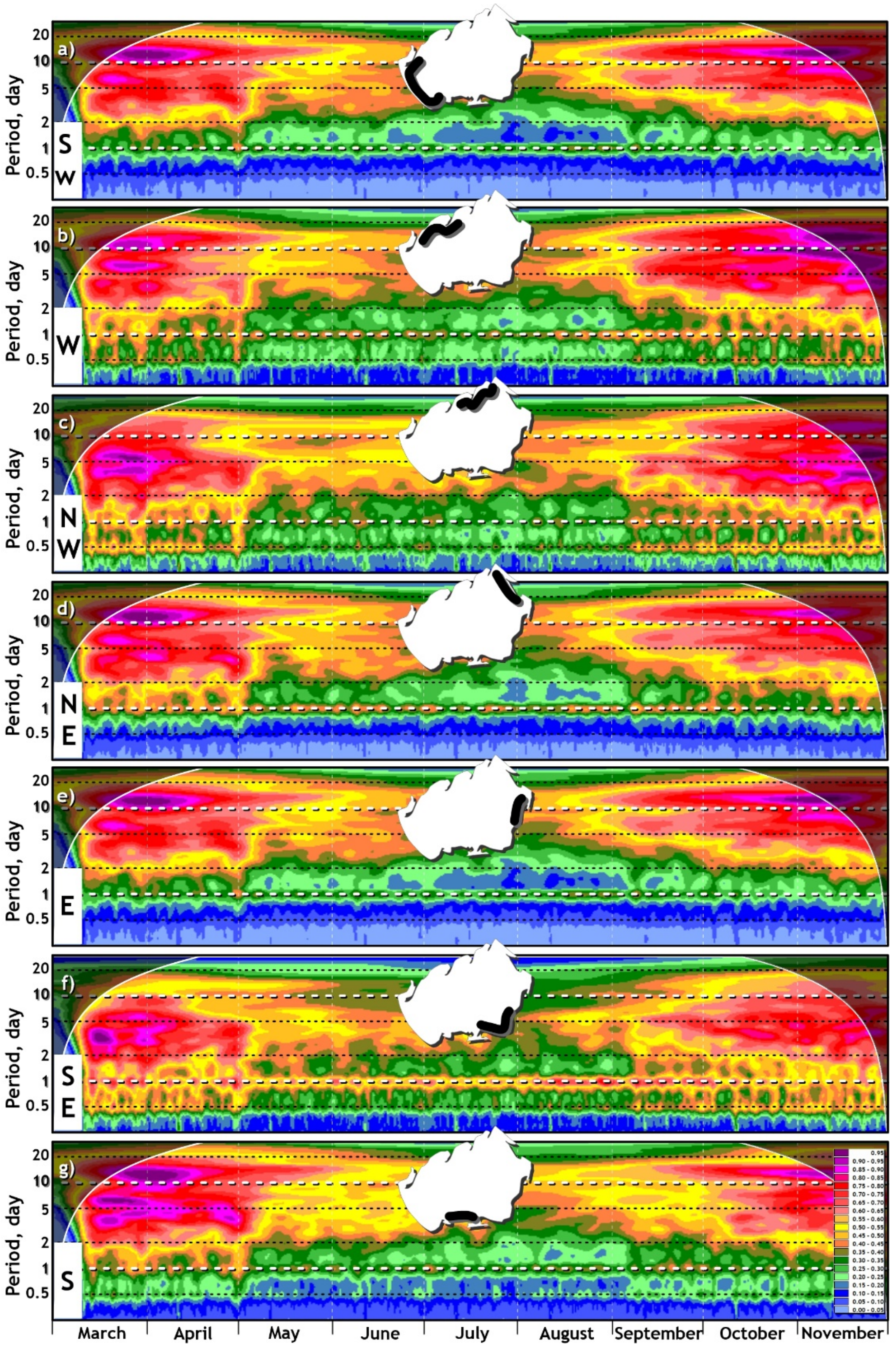
A similar spatial pattern is observed for diurnal fluctuations, but in this case the maximum fluctuations shift to the north for the southwest of the water area and to the south for its northeast. Diurnal fluctuations dominate in the north of the Arabatskaya spit and the Fedotov spit, as well as along the Achuevskaya, Yasenskaya, and Kamyshevatskaya spits.

In the case of semidiurnal fluctuations, the situation is somewhat different (Fig. 6, *h*). The central line of fluctuations runs from the middle of the Arabatskaya Spit through the sea center to the Dolgaya Spit. The maxima of semi-diurnal fluctuations are most pronounced in the western part of the sea between the Fedotov and Obitochnaya spits, and in the eastern part, between the Temryuk Bay and the Yasenskaya Spit.

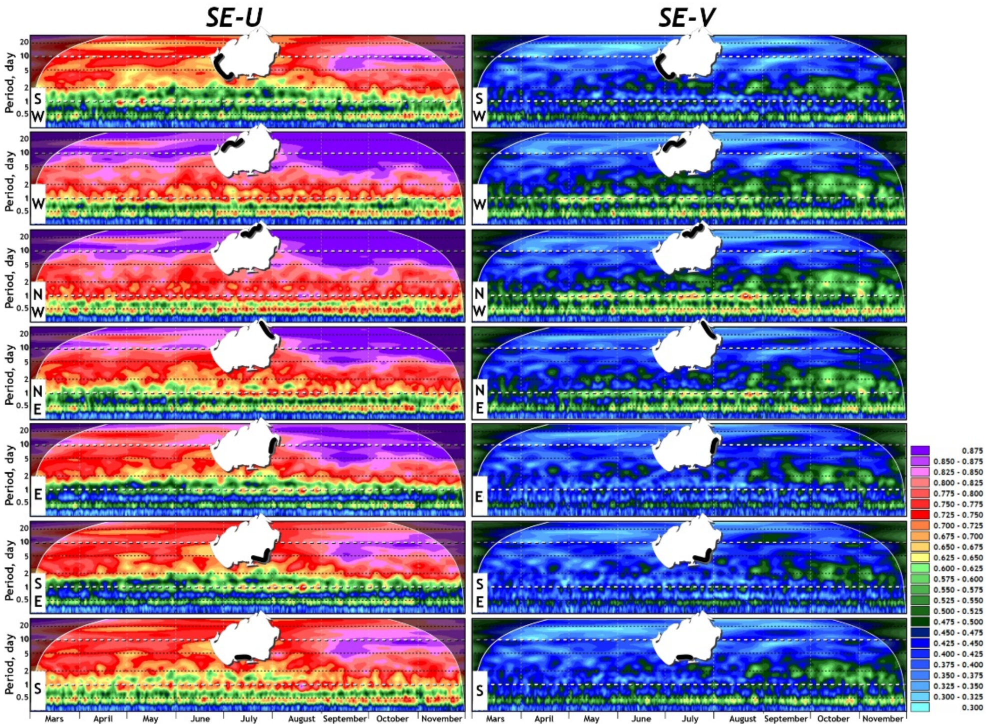
The Sea of Azov level fluctuations have pronounced seasonal variability. Fig. 7 shows averages for the 1979–2020 wavelet spectra of level fluctuations in the coastal zone. For each of the coastal sections, the spectra are normalized to maximum values, which allows evaluating the contribution of spectral components to the formation of the overall spectrum of each specific section.

According to Fig. 7, level fluctuations with periods exceeding two days are observed mainly in the spring-autumn seasons, namely from March to April and from September to November. In this case, the greatest contribution to synoptic variability is made by processes occurring in March and November. The most significant and, characteristically, diurnal fluctuations that are practically season-independent appear in the southeast, and also to a lesser extent in the northeast of the sea. The semidiurnal harmonic is best visible in the spectra of level fluctuations in the western, northwestern, and also the opposite southeastern and southern parts of the sea. At the same time, semidiurnal harmonics are also most pronounced in spring and autumn, weakening significantly in the summer months.

Fig. 8 presents the coherence between sea level fluctuations and horizontal components of surface wind speed. Fig. 8 shows that sea level fluctuations and the zonal wind speed component (*U*) have high coherence coefficients over the entire range of time-frequency variability. At the same time, in autumn the *SE–U* coherence is slightly higher than in the spring and summer months. The highest values of the coherence coefficient of the *SE* and *U* pair are observed at fluctuation periods exceeding 5 days.



F i g. 7. Normalized climatic wavelet spectra of sea level fluctuations



F i g. 8. Coherence between the sea level fluctuations *SE* and the *U*, *V*-components of wind speed

The relationship between level fluctuations and the meridional component of wind speed *V* is manifested in diurnal and semidiurnal cycles. At these temporal scales, the coherence between *SE* and *V* is especially strong in the western, northwestern and northeastern parts of the sea. Unlike the *SE* – *U* pair, the coherence between *SE* and *V* at periods longer than 5 days is quite weak, and at periods shorter than 5 days it is noticeable only in the autumn season.

Conclusions

The present paper is aimed at studying climatic fluctuations in the Sea of Azov level on the synoptic and mesoscale variability scales. The main research method is mathematical modeling using combined hydrodynamic and wave models. The model was verified based on observational data at four coastal hydrometeorological stations (Genichesk, Mariupol, Opasnoe, and Temryuk). The initial data for the analysis are hourly sea level rises from March to November over 42 years (1979 to 2020).

Below, the results of the works carried out are summed up:

1. The main sea level fluctuations in the ranges of synoptic and mesoscale variability are concentrated in the following periods (in days): 0.5; 1; 1.8–2.5; 3–5; 5.5–7; 8.5–11; 12.5–13.5; 14.5–17. In this case, the strongest are fluctuations with periods exceeding 14.5 days. Fluctuations with periods of 12.5–13.5 and 8.5–11 days are smaller in amplitude. The fluctuation powers for periods of 5.5–7 and

3–5 days are almost the same. Fluctuation cycles with periods of 1.8–2.5 days are half as long as daily ones. The weakest are the semi-diurnal fluctuations, which are an order of magnitude smaller than the diurnal ones.

2. Level fluctuations with periods exceeding two days have the form of a single-node seiche with maximum amplitudes in the coastal zone of two opposite areas: in the southwest of the sea (along the Arabatskaya spit) and in the northeast (from the Yasenskaya to the Belosarayskaya spit). Conventionally, the central line of the seiche runs from the Temryuk Bay through the sea center to the bay between the Obitochnaya and Berdyanskaya spits. The same patterns are also characteristic of diurnal fluctuations, but in this case the maximum fluctuations shift to the north for the southwest of the water area and to the south for its northeast. Diurnal fluctuations dominate in the north of the Arabatskaya spit and the Fedotov spit, as well as along the Achuevskaya, Yasenskaya and Kamyshevatskaya spits. In the case of semi-diurnal fluctuations, the picture changes. The central line of fluctuations runs from the middle of the Arabatskaya Spit through the sea center to the Dolgaya Spit. The maxima of semi-diurnal fluctuations are most pronounced in the western part of the sea (in the bay between the Fedotov and Obitochnaya spits) and in its eastern part (between the Temryuk Bay and the Yasenskaya Spit).

3. Seasonal variability is very typical for fluctuations in the Sea of Azov level. Level fluctuations with periods exceeding two days are observed mainly in the spring-autumn seasons, namely from March to April and from September to November. In this case, the greatest contribution to synoptic variability is made by processes occurring in March and November. Diurnal fluctuations are practically independent of the season. The most significant of them appear in the southeast, and also to a lesser extent in the northeast of the sea. Semidiurnal harmonics are most pronounced in spring and autumn, weakening significantly in the summer months.

4. Sea level fluctuations and a zonal component of wind speed have high coherence coefficients over the entire range of time-frequency variability. The highest values of the coherence coefficient are observed at fluctuation periods exceeding 5 days.

5. The relationship between level fluctuations and the meridional component of wind speed is mainly manifested in diurnal and semidiurnal cycles. The coherence between them at periods longer than 5 days is rather weak, and at periods less than 5 days it is noticeable only in the autumn season.

A small comment. The results obtained are based on numerical simulations. The quality of the model ultimately depends on the completeness of taking into account the physical processes that form the sea level surface. A combined hydrodynamic model that takes into account atmospheric pressure fluctuations, direct wind influence, surface waves, wave and storm surges, and tidal movements was used. Outside the scope of the model are river flow, thermal characteristics of the aquatic environment, and atmospheric conditions (temperature, humidity, cloudiness, solar radiation), which undoubtedly influence the Sea of Azov level.

However, as our studies have shown, it is wind and pressure that determine sea level fluctuations in the ranges of synoptic and mesoscale variability.

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Boris V. Divinsky – initiation of research; formulation of goals and objectives of the study; analysis of materials on the research topic; correction of mathematical model and carrying out calculations; processing and description of research results; preparation of the initial version of the text

Vladimir V. Fomin – formulation of goals and objectives of the study; correction of mathematical model and carrying out calculations; qualitative analysis of the results and their interpretation; processing and description of research results; preparation of the initial version of the text

Ruben D. Kosyan – formulation of goals and objectives of the study; general scientific management of research; analysis and generalization of research results; revision of the text

Nikolay N. Dyakov – qualitative analysis of the results and their interpretation; processing and description of research results

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