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Original article

Climatic Spectra of the Fluctuations of Current Velocities and Surface Elevation in the Sea of Azov Based on Numerical Modeling Data

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Abstract
Purpose. The purpose of the study is to analyse the spectral structure of fluctuations in current velocities and sea level elevations in the Sea of Azov over a climatic period, to reveal the spatial and seasonal features of these fluctuations in the mesoscale and synoptic ranges (from hours to dozens of days), as well as to assess the intra-annual variability of current velocities in the central part of the sea.
Methods and Results. The primary research method consisted of numerical modeling which involved a unified hydrodynamic model taking into account the interrelationships between wind waves, currents, and sea level under shallow water conditions. The model was previously verified using the experimentally obtained sea state parameters. The required hydrodynamic parameters were calculated for a 46-year climatic period (1979–2024). The output data consisted of three-dimensional spatial fields of current velocity components and sea level in the Sea of Azov at a 1 h resolution. The main periods of hydrodynamic parameter oscillations – 0.5, 1, 3.6–4.2, 5.6–7.1, and 13.6–14.8 days – were identified based on spectral analysis. The energy of fluctuations increased with the period; two-week fluctuations were the most intense. The power of current velocity fluctuations in the surface layer was 2–3 times higher than that in the bottom layer. At periods exceeding one day, the velocity fluctuations of surface and bottom currents slightly dominated in spring, whereas sea level fluctuations at periods of 5.6–7.1 and 13.6–14.8 days were maximal in autumn, and those at periods of 3.6–4.2 days were maximal in spring. For all the parameters, diurnal fluctuations were maximal in summer, and semidiurnal ones in autumn. The spatial distribution of sea level fluctuations exhibited clear zonality: the highest amplitudes at periods exceeding 3 days were observed in the northeastern and southwestern parts of the sea, at diurnal periods in the eastern and western parts, and at semidiurnal periods in the southeastern and northwestern parts. In the central part of the sea, two peaks were well pronounced in the spectrum of the meridional velocity component: the annual (dominant) and semi-annual ones; in the zonal component, a 0.7-year period (~ 260 days) was added to them. In the frequency spectra, the low-frequency fluctuations (~ 2 and 4 years) were weakly pronounced.
Conclusions. The obtained spectral characteristics demonstrate the response of the shallow Sea of Azov to atmospheric forcing. The spatial and seasonal variability of fluctuations can be used both for verifying the hydrodynamic models and for assessing the climatic variability of currents in the region.

Keywords: Sea of Azov, numerical modeling, currents, sea level fluctuations, climate, spectra

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Introduction

The hydrodynamic regime of any sea area is primarily determined by currents, wind waves, and sea level fluctuations, which are formed under the influence of the geographical location of the area, bathymetric features, and atmospheric conditions. For the Sea of Azov, free surface fluctuations have been studied most extensively, facilitated by a wide network of coastal hydrometeorological stations that conduct continuous monitoring of sea level. The body of literature on this issue is large; without diminishing the contribution of other authors, we note the works [1–12]. Owing to the development of spectral wave models, the wave regime of the sea has also been studied quite well [13–18].

As a rule, studies of currents in the Sea of Azov were devoted to specific problems, such as the analysis of particular conditions for the formation of the current field under the influence of winds from certain directions or individual storms [1] [19–23]. In [24] the results of *in situ* observations performed in 2023–2024 are summarized, several hydrodynamic situations characterising the circulation features of the Sea of Azov are described, and tidal components in the spectra of current velocity fluctuations are identified.

Given the lack of data from direct instrumental measurements of current parameters, numerical modeling serves as a natural alternative, allowing for the acquisition of long and continuous series of current characteristics across the entire sea area. In [25], the results of calculating current parameters over a 45-year climatic period (1979–2023) are presented, and the three-dimensional spatial structure of currents in the Sea of Azov is established.

The principal purpose of the present study is to analyse the spectral structure of fluctuations in current velocities and sea level elevations in the mesoscale and synoptic ranges of variability (from hours to dozens of days), to reveal the spatial and seasonal features of fluctuations in these hydrodynamic parameters, as well as to assess the possible intra-annual and interannual variability of current velocities in the central part of the sea.

Materials and methods

Model and materials used

Two key morphological and hydrological features of the Sea of Azov that directly affect the accuracy of numerical modeling results should be highlighted: 1) extensive shallow-water areas, for which the calculated sea level values are comparable to local depths; 2) the possibility of the formation of an ice cover in winter.

The former circumstance leads to the interdependence of the parameters of currents, sea level elevations, and wind waves, which is accounted for through a unified hydrodynamic model. Current characteristics are calculated using the 5-layer σ-coordinate hydrodynamic model ADCIRC, and wind waves are calculated using the spectral wave model MIKE 21 SW. In this approach, wind wave parameters are determined taking into account the current velocities and directions,

[1] Popov, S.K., 2018. [*Modeling and Prediction of Changes in Sea Level and Current Velocities in the Russian Seas*]. DSc. Dissertation in Physics and Mathematics. Moscow, 300 p. (in Russian).

as well as sea level elevations; the current fields are corrected for the radiation stresses arising from wave breaking. The initial meteorological fields (wind speed, surface atmospheric pressure, and ice concentration) are obtained by sampling the ERA5 global reanalysis dataset. The spatial step in latitude and longitude is 0.125°, the temporal step is 3 h for wind speed and pressure, and 1 day for ice concentration.

The model was previously verified using the available observational data on the parameters of currents, sea level, and wind waves obtained from instrumental measurements (pressure sensors, ADCPs, and Vector-2 current meters), as well as from satellite observations. The verification stages are detailed in [26].

Accounting for ice cover

The problem of ice cover requires more detailed consideration, as it significantly affects currents and wave fields. Climatic aspects of ice formation have been considered in numerous studies [27–31]. In particular, these studies have shown that:

1) The maps of the spatial distribution of ice over the sea area differ (sometimes significantly) depending on the method of obtaining and analysing satellite information. In other words, the choice of the database used in modeling current fields is inevitably subjective, since it is impossible to compare data, for example, from reanalyses for a specific period with observations that could be regarded as reference data (especially in the open sea). It should be noted that at least daily fields of ice cover are needed for modeling;

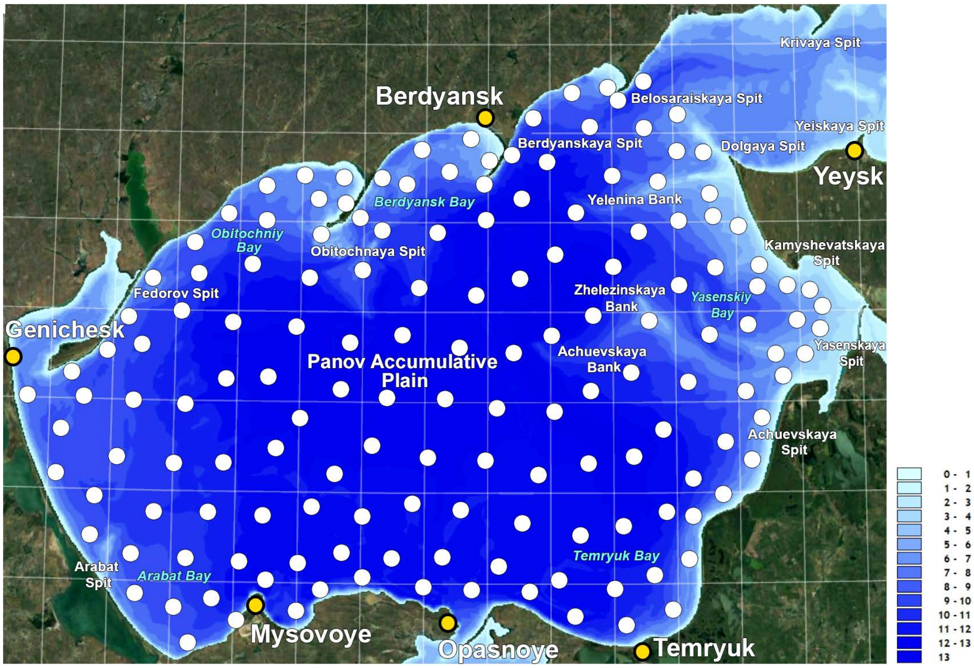
2) For the Sea of Azov, the frequency of severe winters, determined by the sum of sub-zero air temperatures, is 17% [28]. During such winters, almost the entire sea area is covered with ice of varying concentration. In moderate (frequency: 46%) and mild (frequency: 37%) winters, the ice cover is concentrated, as a rule, in Taganrog Bay and in shallow-water areas along the perimeter of the sea. Thus, ice is almost always present in Taganrog Bay in winter.

The procedures for averaging current fields over a long period are less sensitive to the accuracy of the input data and can accommodate gaps and missing data over certain periods more readily than can spectral analysis, which requires continuous time series of current velocities. Since errors in the input ice-cover fields are most significant for the shallow Taganrog Bay, and because of possible uncertainties in satellite reanalyses, the spectral analysis of fluctuations in current velocities and sea level elevations was carried out only for points within the main body of the sea for the nominally ice-free period from March to November.

Selection of calculation points and data processing

The hydrodynamic parameters of the Sea of Azov were calculated for a 46-year climatic period (1979–2024). The output data consisted of three-dimensional spatial fields of current velocity components and sea level elevations in the Sea of Azov at a 1 h resolution.

Across the sea area, 155 calculation points were selected (Fig. 1); their locations correspond to depths equal to or exceeding 4 m. For each of these points, 46 annual time series of current velocities in the surface and bottom layers, as well as sea level elevations, were formed for the entire period from March to November and separately for each season (spring, summer, and autumn) in each year from 1979 to 2024.



F i g. 1. Location of calculation points in the Sea of Azov

Spectral analysis

Spectral estimates were obtained using Welch's periodogram method, implemented in the Matlab environment. This method uses a weighting function to prevent spectral leakage and reduce the bias of the resulting estimate of spectral components, and splits the original signal into overlapping segments, which increases the total number of segments and reduces the variance of the estimate.

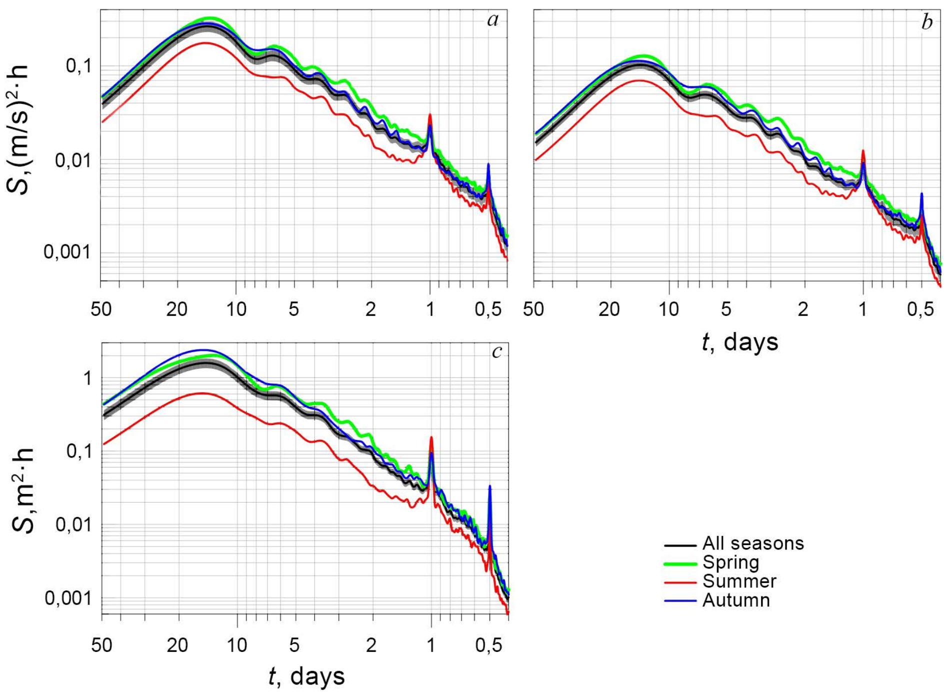
The 46 spectra obtained for each point were then averaged over the entire ice-free period, as well as for each season, yielding climatic mean annual estimates of the spectral density of fluctuations in current velocities and sea level elevations.

It should also be noted that, as a rule, it is not the velocity magnitude itself that is subjected to spectral analysis, but its components – either geographic (northward and eastward) or projections onto the alongshore and cross-shore axes. For local applications involving specific coasts, such an approach is fully justified, but in our case, when considering the entire sea area, it is preferable to analyse the velocity magnitudes themselves for ease of interpretation.

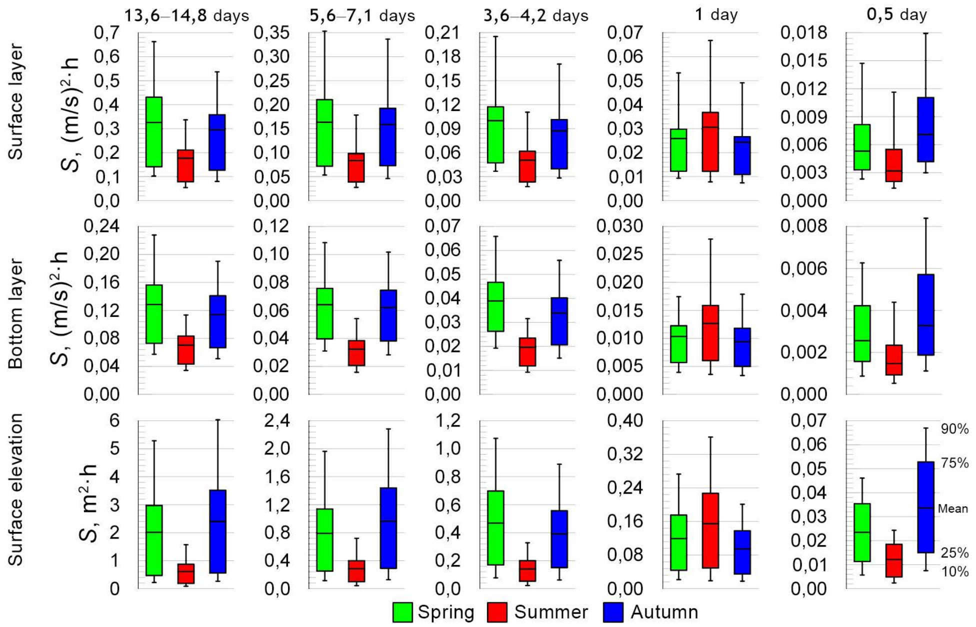
Hereinafter, the term 'frequency spectra' refers to the mean annual (i.e. climatic) spectra of fluctuations in hydrodynamic parameters, obtained by averaging over 46 years.

Results and discussion

Fig. 2 and 3 show the spectra of fluctuations in current velocities in the two layers under consideration, respectively, as well as the spectra of fluctuations in sea level elevations, all averaged over the 155 points across the sea.



F i g. 2. Frequency spectra of current velocity fluctuations in the surface (*a*) and bottom (*b*) layers, as well as sea level fluctuations (*c*). Gray shading shows the 95% confidence intervals



F i g. 3. Interannual statistical characteristics of spectral densities of hydrodynamic parameter fluctuations

As revealed by the spectral analysis, the mesoscale and synoptic variability was characterised by the main peaks in oscillations of current velocities and sea level elevations at periods of 0.5, 1, 3.6–4.2, 5.6–7.1, and 13.6–14.8 days (Figs. 2 and 3). The energy of fluctuations increased with the period: two-week fluctuations were the most intense, and semidiurnal ones were the least intense, although they were still clearly pronounced. The power of current velocity fluctuations in the surface layer was 2–3 times higher than that in the bottom layer.

The diurnal and semidiurnal harmonics are well pronounced in the **experimental** spectra of sea level fluctuations in the Sea of Azov [12, 24]. The same fluctuations have been found in the Baltic Sea [32] and the Black Sea [33]. Worldwide, the spectra of current velocities have been studied to a much lesser extent, which is primarily due to the technical difficulties involved in conducting long-term experiments. Two hydrophysical test sites have played an important role in the history of experimental studies of currents: that of the Shirshov Institute of Oceanology, Russian Academy of Sciences (on the northeastern shelf of the Black Sea near Gelendzhik) and that of Marine Hydrophysical Institute (Katsiveli, Crimea). Observations conducted by the Shirshov Institute of Oceanology in 2016–2023 established that the characteristic periods of coastal current velocity fluctuations were 1, 2.2, and 5 days [34]. The processing of data obtained by Marine Hydrophysical Institute in 2002–2023 allowed the following periods of velocity fluctuations to be identified: 0.5, 1, 3.5, 6, and 12 days [35, 36]. In Lake Ontario, USA (characteristic dimensions of 300 × 90 km), the analysis of data from a bottom-mounted ADCP for April–October 2018 revealed current velocity fluctuations at periods of 1, 5.2, 6.8, and 10.5 days [37]. Analysis of ADCP data from the southern part of the Caspian Sea for 2017–2018 revealed velocity fluctuations with periods of ~ 0.5, 1, ~ 2, and ~ 7 days [38]. Thus, the periodicities of fluctuations in hydrodynamic parameters identified for the Sea of Azov by numerical methods are common to many water bodies worldwide.

Fluctuations in current velocities and sea level have pronounced seasonal features. Fig. 3 presents box-and-whisker plots characterising the interannual variations in the spectral densities of fluctuations at the main periods of variability for each season.

The plots were constructed based on the statistical processing of 46 spectra, each of which was obtained by averaging the spectra for a specific year over the 155 points. The plots show the mean annual values, as well as the 10th, 25th, 75th, and 90th percentiles of the distributions.

The main features of seasonal fluctuations in the mesoscale and synoptic ranges of variability are as follows (Fig. 3):

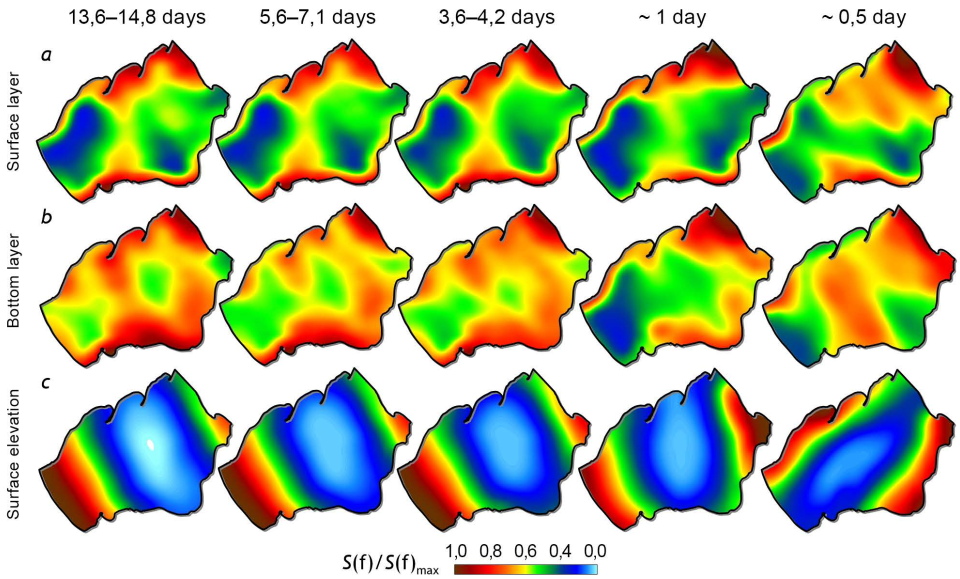
– In spring, fluctuations in surface and bottom current velocities are slightly more pronounced at periods exceeding 1 day (3.6–4.2, 5.6–7.1, and 13.6–14.8 days);

– In autumn, sea level fluctuations are strongest at periods of 5.6–7.1 and 13.6–14.8 days, and in spring at periods of 3.6–4.2 days;

– For both current velocities and sea level, diurnal fluctuations are maximal in summer, whereas semidiurnal ones are maximal in autumn.

It should be clarified that the box plots characterise the interannual variability of the fluctuations: the coloured rectangles in Fig. 3 contain 50% of the sample, whereas the interval between the extreme percentiles contains 80%. A substantial interannual range of fluctuations in spring and autumn is clearly visible across the entire range of periods considered. In summer, the largest interannual range is observed for diurnal fluctuations.

The spatial distributions of **mean annual** (over 46 years) spectral density values at the main periods of fluctuations in current velocities in the surface and bottom layers, as well as in sea level elevations, are shown in Fig. 4. These distributions show that the strongest current velocity fluctuations at periods of one day or more are observed along the northern and southern coasts, as well as in the band passing through the centre of the sea. This band corresponds to the western periphery (for surface currents) and eastern periphery (for bottom currents) of a large cyclonic gyre, which is a key feature of the climatic water circulation in the Sea of Azov. The pattern of semidiurnal fluctuations in current velocities is more spatially heterogeneous and primarily reflects the response of the marine environment to rapid changes in external conditions. The spatial distributions of sea level fluctuations reveal clear zonality. The highest amplitudes at synoptic periods (greater than three days) are observed in the northeastern and southwestern parts of the sea; those of diurnal fluctuations are observed in the eastern and western parts, and those of semidiurnal fluctuations are observed in the southeastern and northwestern parts. The angle between the notional axes separating these areas for the periods of 13.6–14.8 and 0.5 days is ~ 70°. Thus, significant differences are observed between the synoptic and mesoscale responses of the Sea of Azov water area to external forcing.



F i g. 4. Annual average values (normalized to maximum ones) of the energy of spectral fluctuations of current velocities in the surface (*a*) and bottom (*b*) layers and sea level (*c*)

Under the shallow-water conditions of the Sea of Azov, the elements of three-dimensional water circulation (mean and wave-induced currents, storm surges, and seiche oscillations) are formed mainly under the influence of atmospheric conditions, namely wind parameters and surface atmospheric pressure. Other forcing factors (river runoff, water stratification, etc.) also contribute, but accounting for them would require a broader problem formulation and is beyond the scope of the present study.

Wind characteristics (speed and direction) and pressure very among regions of the Sea of Azov. Nevertheless, to assess the climatic variability of meteorological fields, it is acceptable to use data from a single point in the centre of the sea.

Fig. 5 shows the wind roses for the centre of the sea for the ice-free period from 1979 to 2024, as well as for individual seasons. The roses are plotted using data from the ERA5 reanalysis. As shown in Fig. 5, from March to November, north-easterly winds prevail (25%); winds from the south-east and south are observed quite rarely (4 and 8%, respectively); and the frequency of winds from each of the remaining directions is ~12–13%. In spring, the frequency of southerly and south-westerly winds increases (17 and 13%, respectively). In summer, north-easterly winds dominate (almost 30%), while the frequency of winds from the north (19%) and north-west (14%) increases, and that of winds from the east decreases (to 7%). The main feature of the wind regime in autumn is an increase in the frequency of winds from the east (to 18%) and a high frequency of strong westerly and north-westerly winds (with speeds exceeding 15 m/s). These results are consistent with the conclusions presented in study [2] and are based on NCEP/NCAR reanalysis data.

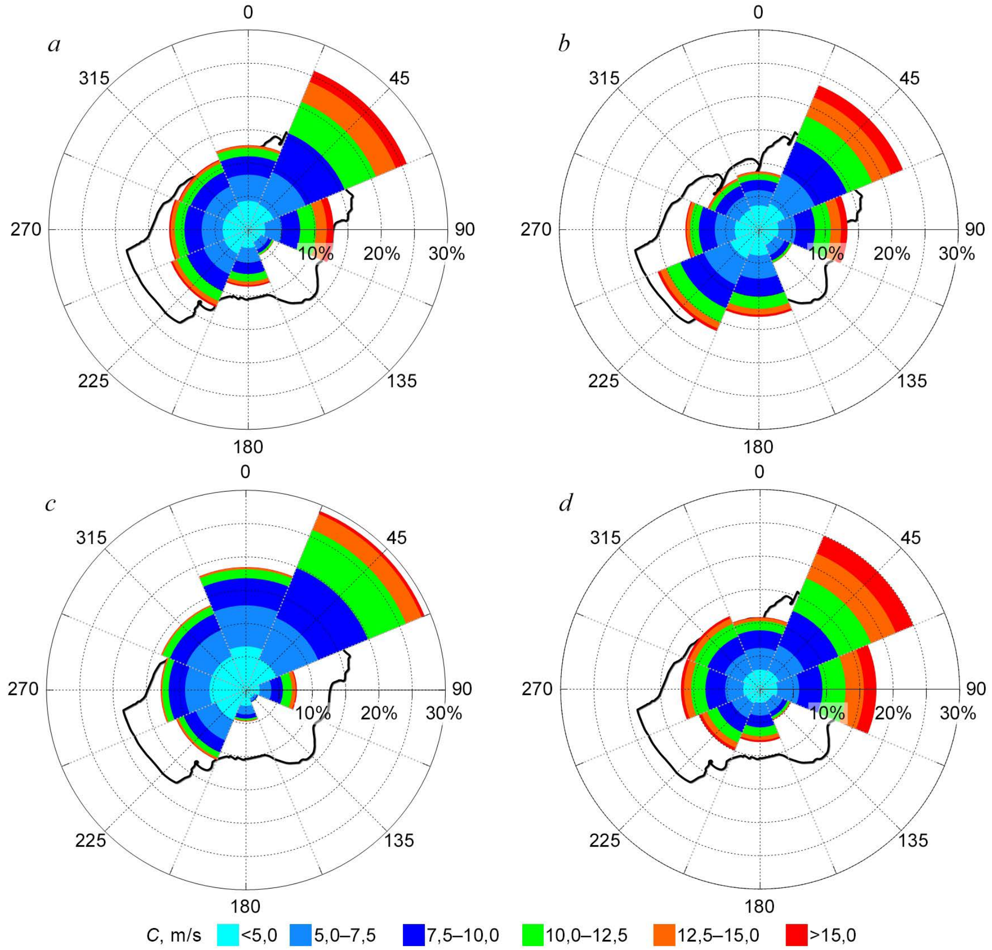
Thus, the dominant wind forcing over the Sea of Azov acts along the NE–SW and NW–SE axes. Based on the obtained spatial distribution maps of sea level fluctuation energy (see Fig. 4, *c*), the mean frequency spectra of the two wind velocity components were constructed, together with the spectrum of surface atmospheric pressure fluctuations in the centre of the sea (Fig. 6).

As the data in Fig. 6 show, all the previously identified oscillation periods are present in the spectra of wind velocity and atmospheric pressure, including the diurnal and semidiurnal cycles; the powers of atmospheric pressure fluctuations at periods of 1 and 0.5 days are similar. The diurnal and semidiurnal harmonics are also clearly apparent in the wind velocity spectra for the southern coast of Crimea [35]. A comparison of the oscillation energy along the 60–240° and 310–130° axes is presented in Fig. 7, which shows the ratios of the mean annual spectral powers of fluctuations in the wind components V_r and U_r.

As shown in Fig. 7, at synoptic timescales (periods greater than 2–3 days), the power of wind velocity fluctuations along the 60–240° axis, extending from the Dolgaya Spit in the northeastern part of the sea to the Arabat Spit in the southwestern part, significantly exceeds. At periods shorter than 2 days, the oscillation energy along the 60–240° and 310–130° axes is comparable, except for the diurnal cycle. In spring and summer, the diurnal fluctuations are determined almost entirely by airflow from NE to SW (Fig. 7, *b*, *c*); in autumn, this dominance is less noticeable (Fig. 7, *d*). The contribution of winds oriented along the NW–SE axis (310–130°) to the semidiurnal harmonics is dominant both throughout the entire ice-free period from March to November (Fig. 7, *a*) and in spring and autumn separately (Fig. 7, *b*, *d*); in summer, the contribution of these winds slightly

[2] Lopatoukhin, L.I., Boukhanovsky, A.V., Ivanov, S.V., and Chernysheva, E.S., 2006. *Reference Data on Wind and Wave Regime of the Baltic, North, Black, Azov and Mediterranean Seas*. Saint Petersburg: Russian Maritime Register of Shipping, 451 p. (in Russian).

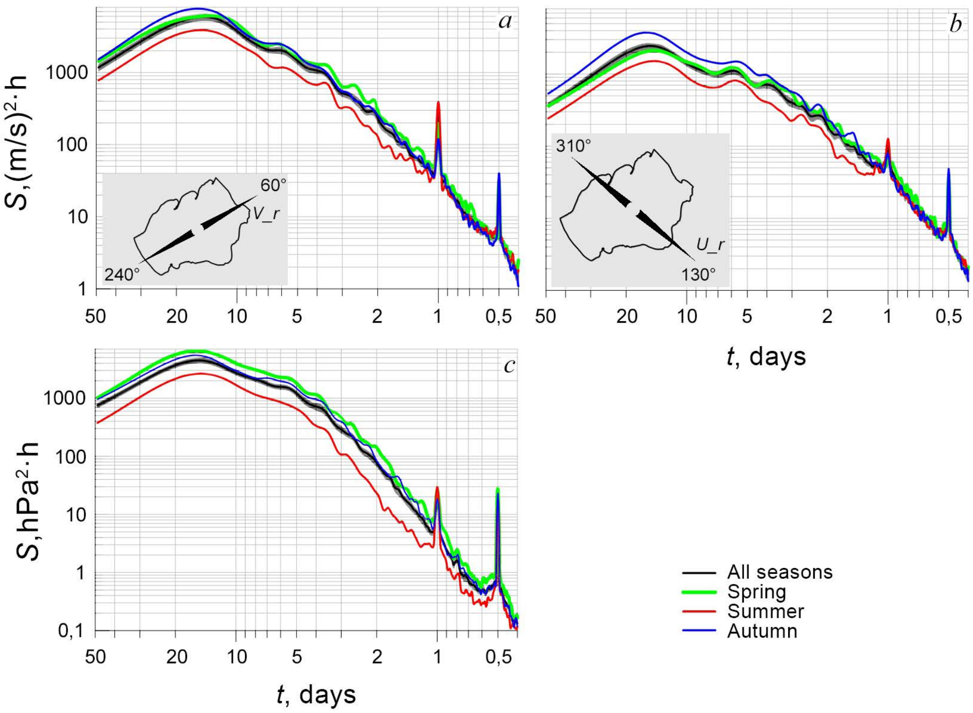
decreases. Thus, the characteristics of wind velocity fluctuations in the frequency domain can serve as a basis for interpreting the spatial maps of the spectral energy of sea level fluctuations (see Fig. 4, *c*) and current velocity fluctuations (see Fig. 4, *a*, *b*). In general, the hydrodynamic response to external forcing is determined not only by atmospheric conditions but also by the coastline configuration and local bathymetry.



F i g. 5. Climatic wind roses for the central sea: *a* – the whole period; *b* – spring; *c* – summer; *d* – autumn

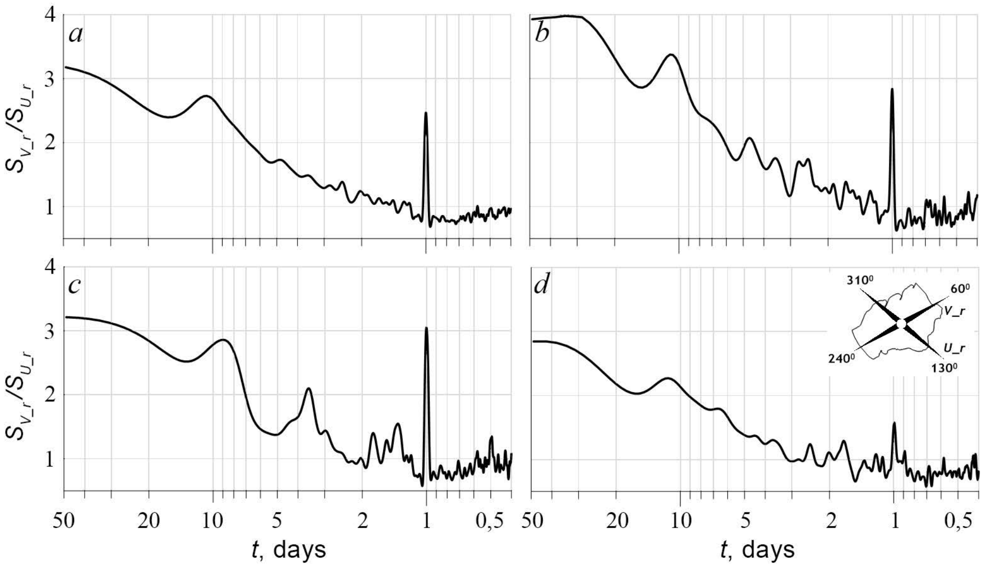
The accumulated array of calculated hydrodynamic parameters of the Sea of Azov over an extended period makes it possible to assess the intra-annual and interannual variability of current velocities. For this purpose, a point in the centre of the sea was selected, and time series of the daily mean eastward and northward components of surface current velocity were constructed for 1970–2024. As already mentioned, severe winters with ice cover of varying intensity in the central part of the sea are relatively infrequent. Daily averaging and autoregressive gap filling made it possible to obtain continuous velocity time series, albeit with some uncertainty.

In our opinion, the limitations of this approach are offset by the opportunity to obtain a broader perspective on the climatic variability of currents. It is also useful to complement the study with an analysis of the time–frequency variability of selected characteristics of global atmospheric circulation. Since these characteristics describe the state of the same system, namely the atmosphere, they are often interrelated. Accordingly, two indices characterising large-scale atmospheric circulation in the Northern Hemisphere were selected: The North Atlantic Oscillation (NAO) and the Scandinavian pattern (SCAND). Their daily values are available from the NOAA Climate Prediction Centre (available at: http://www.cpc.ncep.noaa.gov). These indices were selected because they characterise the prevailing meridional (NAO) and zonal (SCAND) air mass flows over the Sea of Azov.



F i g. 6. Annual average frequency spectra of fluctuations of wind speed components: projections onto the axes 60–240° (*V_r*) (*a*) and 310–130° (*U_r*) (*b*), as well as atmospheric pressure (*c*). Gray shading shows 95% confidence intervals

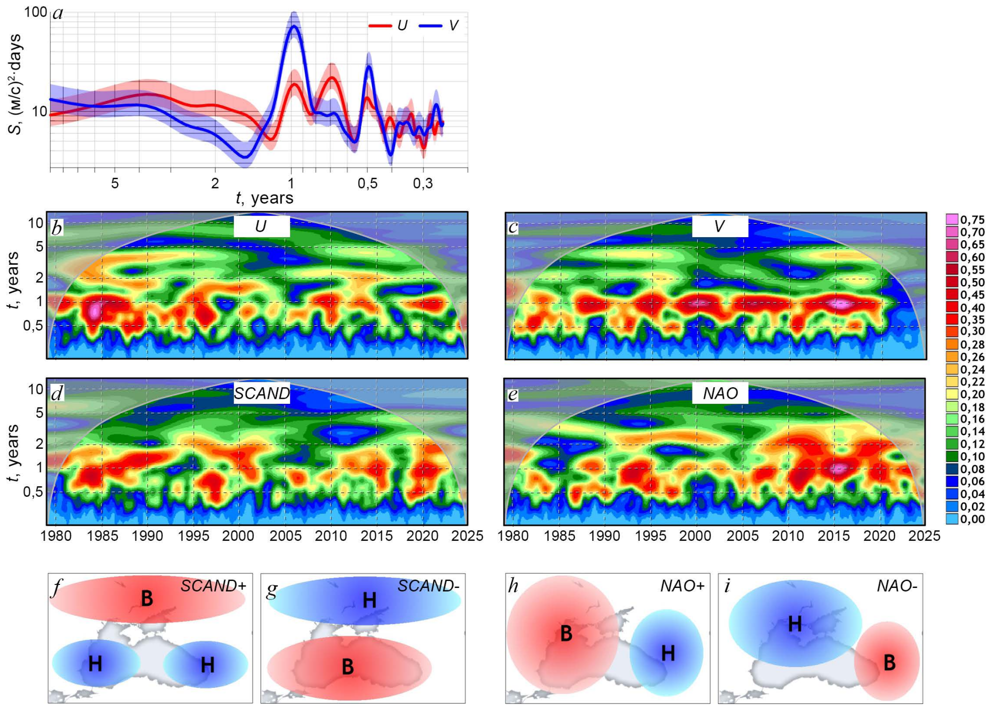
Fig. 8 presents the frequency spectra of the *U*- and *V*-components of velocity, the wavelet spectra (scalograms) of the velocity components and atmospheric circulation indices, and, in **schematic** form, the position of high (*H*) and low (*L*) atmospheric pressure systems during the positive and negative phases of the large-scale oscillations. The following points should be noted: 1) the pronounced non-stationarity of the index time series makes their conventional frequency spectra highly sensitive to spectral-analysis settings (segment length, degree of window overlap, etc.); in other words, the frequency spectra of the index fluctuations provide little useful information and are therefore not presented; 2) the scalograms display the continuous wavelet power, with the colour scale representing its magnitude; 3) the grey area in Fig. 8, *b–e*, denotes the so-called cone of influence, i.e. the region affected by edge effects of the transform, within which the results may be unreliable.



F i g. 7. Ratio of the amplitudes of wind speed component fluctuations: *a* – the whole period; *b* – spring; *c* – summer; *d* – autumn

As shown in Fig. 8, two distinct peaks are present in the spectrum of the northward (meridional) velocity component: the dominant annual peak and a semi-annual peak. The spectrum of fluctuations in the eastward (zonal) component contains three maxima with **comparable** oscillation energies: in addition to the annual and semi-annual periods, a peak occurs at 0.7 years (~ 260 days). Lower-frequency fluctuations (~ 2 and 4 years) are only weakly apparent in the frequency spectra but are clearly evident in the wavelet spectra during certain periods, for example, in the *U*-component in 1982–1992 (Fig. 8, *b*), and in the *V*-component in 2015–2020 (Fig. 8, *c*).

Large-scale changes in atmospheric circulation are too complex for a strong relationship to be expected between atmospheric circulation indices and fluctuations in current velocity within a relatively small individual water body. For example, study [39] considers a correlation coefficient of 0.4 between maximum wave heights in the Black Sea and selected atmospheric circulation indices to be reasonably strong. Nevertheless, in the present study, the NAO index exhibits a relatively stable annual cycle (Fig. 8, *e*), which corresponds to the annual harmonic of the meridional current velocity component (Fig. 8, *c*), particularly during 2010–2020. In the interpretation adopted here, for the Sea of Azov, fluctuations in the NAO index are associated with the transport of air masses from north to south during its positive phase and in the opposite direction during its negative phase (this represents a generalized picture rather than a strict regularity). In the case of a pronounced zonal transport, for which fluctuations in the SCAND index are used as a relative indicator, fluctuations in the eastward velocity component intensify, as observed, for example, in the periods 1983–1987 and 2017–2023 (Fig. 8, *b*, *d*). Thus, the existence of an annual cycle in current velocities in the Sea of Azov, despite the simplifying assumptions involved, can be considered reasonably well supported.



F i g. 8. Frequency spectra of fluctuations of current velocity components in the center of the sea (translucent colored areas correspond to the 95% confidence intervals) (*a*), wavelet spectra of *U*- (*b*) and *V*-components (*c*) of current velocity and atmospheric circulation indices *SCAND* (*d*) and *NAO* (*e*); schematic representation of the positive (*f*, *h*) and negative (*g*, *i*) phases of *SCAND* (*f*, *g*) and *NAO* (*h*, *i*). Letters "H" and "L" indicate the areas of high and low values, respectively

Conclusions

Among the hydrodynamic characteristics of the seas of the World Ocean, the most studied from a climatic point of view are sea level (owing to the wide network of *in situ* observations) and wind waves (due to the relative simplicity of their numerical modeling). Sea currents are formed under the influence of a complex of factors, and their study (experimental and numerical) involves many difficulties. In this regard, the semi-enclosed shallow Sea of Azov represents a convenient object of study. The unified hydrodynamic model used in the present work has made it possible to calculate the current parameters over a long period – from 1979 to 2024. We are not aware of similar results obtained for other seas. Let us note an important circumstance: the model does not guarantee absolute correspondence, for example, between the instantaneous velocity value at a specific point and the measured value. It is a question of statistical (generalized) similarity. As previous studies have shown, even in the presence of uncertainties (unaccounted-for river runoff, for example, and errors in the input data on ice concentration), the obtained results can be interpreted quite well from a physical viewpoint.

The principal purpose of the work was to analyse the periods of fluctuations in current velocities and sea level elevations in the mesoscale and synoptic ranges of variability, as well as to assess the possible intra-annual variability in current velocities in the centre of the sea.

The main results are described below:

1. The mesoscale and synoptic variability is characterised by major peaks in the fluctuations of current velocities and sea level elevations at periods of 0.5, 1, 3.6–4.2, 5.6–7.1, and 13.6–14.8 days.
2. The energy of fluctuations increases significantly as the period increases. Two-week fluctuations are the most intense, whereas semidiurnal ones are the weakest.
3. The power of current velocity fluctuations in the surface layer is 2–3 times higher than that in the bottom layer.
4. At periods exceeding 1 day, fluctuations in surface and bottom current velocities are slightly more pronounced in spring.
5. At periods of 5.6–7.1 and 13.6–14.8 days, sea level fluctuations are strongest in autumn; at periods of 3.6–4.2 days, they are strongest in spring.
6. Diurnal fluctuations of both current velocities and sea level elevations are maximal in summer, whereas semidiurnal ones are maximal in autumn.
7. Maximum current velocity fluctuations at periods of one day or more are observed along the northern and southern coasts, as well as in the band of mean currents passing through the centre of the sea, which corresponds to the western periphery (for surface currents) and eastern periphery (for bottom currents) of a large cyclonic gyre – a key feature of the climatic water circulation in the Sea of Azov.
8. The spatial distributions of sea level fluctuations exhibit clear zonality. The highest amplitudes are observed in opposite parts of the sea: at synoptic periods (greater than 3 days) – in the northeast and southwest of the sea; at diurnal periods – in the east and west; at semidiurnal periods – in the southeast and northwest.
9. In the centre of the sea, two peaks stand out in the spectrum of the meridional velocity component: the dominant annual peak and a semi-annual peak; in the spectrum of the zonal component, an additional peak occurs at 0.7 years (~ 260 days). Low-frequency fluctuations (~ 2 and 4 years) are weakly expressed in the frequency spectra.

REFERENCES

1. Eremeev, V.N., Konovalov, A.V., Manilyuk, Yu.V. and Cherkesov, L.V., 2000. Modeling of Long Waves in the Sea of Azov Generated by Cyclone Propagation. *Oceanology*, 40(5), pp. 616-623.
2. Filippov, Yu.G., 2012. Natural Fluctuations of the Sea of Azov Level. *Russian Meteorology and Hydrology*, 37(2), pp. 126-129. https://doi.org/10.3103/S1068373912020082
3. Fomin, V.V. and Polozok, A.A., 2013. [Technology for Modelling Storm Surges and Wind Waves in the Sea of Azov on Unstructured Grids]. In: MHI, 2013. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources*. Sevastopol: ECOSI-Gidrofizika. Iss. 27, pp. 139-145 (in Russian).
4. Ivanov, V.A., Cherkesov, L.V. and Shul'ga, T.Ya., 2015. Studies of Free Fluctuations of the Sea of Azov Level Arising after the Termination of Prolonged Wind Effect.

Physical Oceanography, (2), pp. 14-23. https://doi.org/10.22449/1573-160X-2015-2-14-23
5. Matishov, G.G. and Berdnikov, S.V., 2015. Extreme Flooding in the Don River Delta in Spring 2013. *Izvestiya Rossiiskoi Akademii Nauk. Seriya Geograficheskaya*, (1), pp. 111-118. https://doi.org/10.15356/0373-2444-2015-1-111-118 (in Russian).
6. Cherkesov, L.V. and Shul'ga, T.Ya., 2016. Investigation of the Effect of the Baric Formation Parameters on Free and Forced Oscillations of the Level and Flow in the Sea of Azov. *Physical Oceanography*, (4), pp. 12-24. https://doi.org/10.22449/1573-160X-2016-4-12-24
7. Cherkesov, L.V. and Shulga, T.Ya., 2017. [*Waves, Currents, Surge Processes, and Transformation of Pollution in the Sea of Azov*]. Sevastopol: MHI, 228 p. (in Russian).
8. Lemeshko, E.E. and Polozok, A.A., 2018. Extreme Levels of the Sea of Azov According to Coastal Measurements. *Ecological Safety of Coastal and Shelf Zones of Sea*, (3), pp. 13-21. https://doi.org/10.22449/2413-5577-2018-3-13-21 (in Russian).
9. Popov, S.K. and Lobov, A.L., 2018. Short-Term Forecasts of the Azov Sea Level Variations during the Iceless Period in 2017. *Hydrometeorological Research and Forecasting*, 3(369), pp. 104-118 (in Russian).
10. Ivanov, V.A. and Shul'ga, T.Ya., 2019. The Influence of Atmospheric Fronts on Free and Forced Oscillations of the Water Level in the Sea of Azov. *Doklady Earth Sciences*, 486(2), pp. 737-740. https://doi.org/10.1134/S1028334X1906028X
11. Bespalova, L.A., Tsygankova, A.E., Bespalova, E.V. and Misirov, S.A., 2019. Dangerous Storm Surges and Destruction of the Azov Sea Coasts. *Science in the South of Russia*, 15(2), pp. 29-38. https://doi.org/10.7868/S25000640190204 (in Russian).
12. Korzhenovskaia, A.I., Medvedev, I.P. and Arkhipkin, V.S., 2022. Tidal Sea Level Oscillations in the Sea of Azov. *Oceanology*, 62(5), pp. 585-596. https://doi.org/10.1134/S0001437022050095
13. Fomin, V.V., 2002. Numerical Model of the Circulation of Waters in the Sea of Azov. *Nauchnye Trudy UkrNIGMI*, 249, pp. 246-255 (in Russian).
14. Dyakov, N.N., Fomin, V.V., Martynov, E.S. and Garmashov, A.V., 2010. Wind and Wave Regime of the Sea of Azov. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources*, 22, pp. 228-239 (in Russian).
15. Matishov, G.G., Golubeva, N.I. and Sorokina, V.V., eds., 2011. *Ecological Atlas of the Sea of Azov*. Rostov-on-Don: Southern Scientific Centre of the Russian Academy of Sciences Publishers, 328 p. (in Russian).
16. Fomin, V.V., ed., 2012. [*Atlas of Waves, Currents, and Sea Level in the Sea of Azov*]. Kyiv, 238 p. (in Russian).
17. Evstigneev, V.P., Naumova, V.A., Voskresenskaya, E.N., Evstigneev, M.P. and Lyubarets, E.P., 2017. *Wind and Wave Conditions of the Coastal Zone of the Azov–Black Sea Region*. Sevastopol: IPTS, 320 p. https://doi.org/10.33075/978-5-6040795-0-8 (in Russian).
18. Yaitskaya, N.A., 2020. Mathematical Modelling of Wind Waves in the Sea of Azov. *Proceedings of the Southern Scientific Centre of the Russian Academy of Sciences*, 8, pp. 86-96. https://doi.org/10.23885/1993-6621-2020-8-86-96 (in Russian).
19. Fomin, V.V., Polozok, A.A. and Fomina, I.N., 2015. Simulation of the Azov Sea Water Circulation Subject to the River Discharge. *Physical Oceanography*, (1), pp. 15-26. https://doi.org/10.22449/1573-160X-2015-1-15-26
20. Cherkesov, L.V., Shul'ga, T.Ya., Dyakov, N.N. and Stanichnaya, R.R., 2017. Numerical Study of Storm Surge Processes and Currents of the Sea of Azov during

a Period of Extreme Winds. *Physical Oceanography*, (5), pp. 3-18. https://doi.org/10.22449/1573-160X-2017-5-3-18
21. Matishov, G.G. and Grigorenko, K.S., 2021. Currents of the Azov Sea during the Don River Low-Water Period. *Oceanology*, 61(2), pp. 173-182. https://doi.org/10.1134/S0001437021020132
22. Matishov, G.G. and Grigorenko, K.S., 2022. Dynamics and Thermohaline Structure in the Contact Zones of the Azov Sea. *Doklady Earth Sciences*, 502(1–2), pp. 51-58. https://doi.org/10.1134/S1028334X22020118
23. Matishov, G.G. and Grigorenko, K.S., 2023. Seiche Currents in the Sea of Azov Based on Field Observations. *Oceanology*, 63(1), pp. 27-34. https://doi.org/10.1134/S0001437023010095
24. Grigorenko, K.S., 2025. Currents of the Sea of Azov Based on Measurements and Spectral Analysis. *Doklady Earth Sciences*, 523(1), 14. https://doi.org/10.1134/S1028334X2560690X
25. Divinsky, B.V., 2025. Spatial Structure of Sea Currents in the Sea of Azov Based on Numerical Modeling Data. *Physical Oceanography*, 32(6), pp. 861-870
26. Divinsky, B.V., Kosyan, R.D. and Fomin, V.V., 2021. Climatic Fields of Sea Currents and Wind Waves in the Sea of Azov. *Doklady Earth Sciences*, 501(1), pp. 976-988. https://doi.org/10.1134/S1028334X21090087
27. Matishov, G.G., Berdnikov, S.V., Zhichkin, A.P., Makarevich, P.R., Dzhenyuk, S.L., Kulygin, V.V., Yaitskaya, N.A., Povazhnyi, V.V., Sheverdyaev, I.V. [et al.], 2014. In: SSC RAS, 2014. *Atlas of Climatic Changes in Large Marine Ecosystems of the Northern Hemisphere (1878–2013). Region 1: Seas of the Eastern Arctic; Region 2: Black, Azov, and Caspian Seas*. Rostov-on-Don: Southern Scientific Centre of the Russian Academy of Sciences Publishers, 256 p. (in Russian).
28. Dyakov, N.N., Timoshenko, T.Yu., Belogudov, A.A. and Gorbach, S.B., 2015. [*Ice Atlas of the Black and Azov Seas*]. Sevastopol: ECOSI-Gidrofizika, 219 p. (in Russian).
29. Yaitskaya, N.A. and Magaeva, A.A., 2018. Dynamics of the Ice Regime of the Sea of Azov in the XX–XXI Centuries. *Ice and Snow*, 58(3), pp. 373-386. https://doi.org/10.15356/2076-6734-2018-3-373-386 (in Russian).
30. Puzina, O.S. and Mizyuk, A.I., 2019. [Study of Ice Conditions in the Sea of Azov Based on Satellite Data and Numerical Modelling Results]. In: Marchuk Institute of Numerical MathematicsRussian Academy of Sciences, 2019. *Proceedings of the International Young Scientists School and Conference on Computational Information Technologies for Environmental Sciences (CITES-2019)*. Tomsk: Tomsk Centre for Scientific and Technical Information, pp. 158-162 (in Russian).
31. Dashkevich, L.V., Nemtseva, L.D. and Berdnikov, S.V., 2020. Modelling of the Sea of Azov Long-Term Ice Cover. *Studies of the Southern Scientific Centre of the Russian Academy of Sciences*, 8, pp. 50-60. https://doi.org/10.23885/1993-6621-2020-8-50-60 (in Russian).
32. Medvedev, I.P., 2015. Formation of the Baltic Sea Level Spectrum. *Doklady Earth Sciences*, 463(1), pp. 760-764. https://doi.org/10.1134/S1028334X1507020X
33. Medvedev, I.P., 2024. Variance of Short-Period Sea Level Oscillations in the Black Sea: Seasonal and Interannual Variations. *Physical Oceanography*, 31(1), pp. 59-70.
34. Divinsky, B.V., Kuklev, S.B., Ocherednik, V.V. and Baranov, V.I., 2025. Parameters of Sea Currents on the Northeastern Black Sea Shelf Based on Experimental Data. *Oceanology*, 65(6), pp. 831-843. https://doi.org/10.1134/S000143702570050X
35. Kuznetsov, A. S., 2024. Peculiarities of Interseasonal Variability of Alongshore Wind Circulation and Coastal Currents off the Southern Coast of Crimea. *Ecological Safety of Coastal and Shelf Zones of Sea*, (1), pp. 31-44.

36. Kuznetsov, A.S. and Ivashchenko, I.K., 2025. Long-Term Average Annual Spectral Characteristics of the Coastal Current Long-Period Oscillations off the Southern Coast of Crimea. *Physical Oceanography*, 32(1), pp. 32-45.
37. Hlevca, B., Howell, T., Madani, M. and Benoit, N., 2025. Fine-Scale Hydrodynamic Modeling of Lake Ontario: Has Climate Change Affected Circulation Patterns? *Environmental Modeling & Assessment*, 30(2), pp. 219-239. https://doi.org/10.1007/s10666-024-10003-z
38. Jamshidi, S., 2024. Flow Measurement in the Southern Coast of the Caspian Sea. *Frontiers in Marine Science*, 10, 1219658. https://doi.org/10.3389/fmars.2023.1219658
39. Andreeva, N., Saprykina, Y., Valchev, N., Eftimova, P. and Kuznetsov, S., 2021. Influence of Wave Climate on Intra and Inter-Annual Nearshore Bar Dynamics for a Sandy Beach. *Geosciences*, 11(5), 206. https://doi.org/10.3390/geosciences11050206

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