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Original article

Features of Forming the Alongcoastal Circulation of the Coastal Ecotone Waters nearby the Southern Coast of Crimea

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Abstract
Purpose. The study is aimed at expanding the notions on the features of forming the mode characteristics, vertical structure and interannual variability of the costal ecotone water circulation nearby the Southern coast of Crimea, as well as on the characteristics, conditions and lifetime of bimodal structure of the coastal current directions.
Methods and Results. New scientific results were obtained with the regard for systematizing and analyzing the already published results on the problem under study. The preset tasks were solved using the monitoring data on variability of the coastal current vertical structure for 2002–2021 obtained through a set of domestic current meters installed at the stationary oceanographic platform of the Black Sea Hydrophysical Sub-Satellite Polygon of Marine Hydrophysical Institute. The materials on the currents' vector base which had passed state registration were processed according to the technique developed on the basis of the standard methods of digital filtering and mathematical statistics. It was found that nearby the Black Sea coast, there existed two different modes of water circulation: the stationary monomodal alongcoastal current and the bimodal modulation of the direction of total alongcoastal flow induced by the intense hydrodynamic disturbances. At all the horizons near Cape Kikineiz, the reverse mode of bimodal structure was formed mostly due to the contribution of fluctuations with the periods up to 3 days, which constituted 98%, whereas the contribution of those with the periods 3–4 days was 2%. A significant decrease in the annual average velocity of a monomodal current changed the conditions for a bimodal structure existence in the near-surface layer where the period of oscillations forming a reverse mode, had increased in 2020 to 5 days.
Conclusions. The results obtained expand our notions on the features of the coastal water circulation mode, and on the conditions and characteristics of the coastal current bimodal structure formed near Cape Kikineiz mostly due to a significant contribution (to 91%) of the fluctuations with periods up to 2 days. The prospect for further development both of the research techniques and the possibility of analyzing quantitative estimates of the coastal current variability including the interannual range are demonstrated.

Keywords: Black Sea, coastal zone, Southern coast of Crimea, water circulation, bimodal current direction, empirical distribution function, spectral density

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Introduction

The results of Marine Hydrophysical Institute (MHI) of RAS research on estimating the impact of coastal-shelf zone water dynamics on the functioning and evolution of the Black Sea marine ecosystems contribute to the development of a promising research area, formed as the ecological coastal zone economy [1]. The aim and main directions of such studies of the natural complex were formulated in [2]. The shelf ecosystem includes coastal ecotone ecosystems [3], concentrated in the boundary zone of the land-sea interface, including the shallow coastal strip of the open part of the sea, gulfs, bays and estuaries. Each section of this coastal zone is a separate natural and economic complex due to peculiarities of local water dynamics, levels and pollution types with different rates of accumulation, assimilation and destruction of pollutants in the marine environment. Ensuring optimal conditions of existence and development for this social ecological and economic system is possible only with the rational development of a complex of marine natural resources. Studies of the thermohydrodynamics of waters and creation of adaptive models for managing the balance of consumption and reproduction of natural resources in the ecological and economic systems of the coastal ecotone are necessary to build an integral model for managing environmental activities of the coastal region to ensure its sustainable economic development [1].

In [3] estimates of the anthropogenic load levels on the Crimean coast are given. It is shown that all the Black Sea coast ecosystems are subject to degradation under the influence of pollutants entering the marine environment. At the same time, it was noted that to establish the damage degree caused to the coastal ecosystem, along with an estimation of anthropogenic load level and the ecosystem self-purification ability, information on the transfer and dispersion of pollutants under the conditions of water dynamics intensification in shallow water and exchange processes at the bottom boundary is necessary. The current level of the Black Sea water pollution [4] confirms the relevance and necessity of limiting the pollution flows entering the marine environment, i.e., introduction of ecological regulation of the anthropogenic impact on the marine ecosystem. As noted in [5], the objectively existing property of the normal ecosystem functioning in the marine environment is the predominant importance of the biotic component in the aspect of destruction and deposition of pollutants, which characterizes the reserve ecosystem capabilities, determined using the assimilation capacity concept. The assimilation capacity value depends on many natural and anthropogenic factors; while in [5] three main processes of natural self-purification are recommended for practical assessments. They are hydrodynamic processes, microbiological oxidation and biosedimentation, i.e., water dynamics, along with the inflow, transfer and dispersion of pollutants, directly affects the ecosystem assimilation possibilities.

Contact and remote studies of the dynamics of Crimean coastal waters are being carried out by MHI in the course of creating local coastal ecotone models. At present, studies of the characteristics of the coastal water dynamics most accurately and reliably provide contact methods and tools, where MHI has a fundamental scientific reserve and many years of practical experience [6]. When solving the problem of environmental regulation in the ecological and economic systems of the coastal ecotone, contact monitoring of the coastal water dynamics is the basic link in estimating the impact of changes in natural, climatic and anthropogenic factors on the hydrological and hydrochemical structure stability and self-purification ability of coastal ecosystems.

The specific features of water circulation near the coast depend on the geographical location, the coastline shape and bottom topography, local hydrometeorological and hydrophysical conditions in the land-sea boundary zone. The currents of a narrow shallow coastal strip have different regularities and features of circulation in comparison with the currents of the shelf-slope part. The relevance of studies of coastal water dynamics, along with the problems of the ecological economy of the coastal zone, is due to the needs of coastal navigation and fishing, the mariculture development, hydraulic engineering and recreational services.

The present paper is aimed at developing scientific ideas about the features of the regime characteristic formation, vertical structure and interannual variability of water circulation of the coastal ecotone near the Southern Coast of Crimea, as well as the characteristics, conditions and duration of the bimodal structure phenomenon of coastal current directions. The scientific novelty of the paper consists in the identification of unique reliable empirical knowledge about the dynamics of coastal waters in the Southern Coast of Crimea (SCC) based on the materials of long-term instrumental monitoring of coastal currents.

Materials and methods

A review of publications on the considered problem is carried out and the results of field studies of regional features of coastal water circulation, obtained earlier in various areas of the Black Sea, are systematized. The main regularities of this circulation are considered in the cycle of works [1-8] [7–25]. Based on the results of expeditionary studies near the western coast works [5, 6] [10, 11] were published;

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[5] Bogatko, O.N., 1979. Surface Currents of the Black Sea. In: *Comprehensive Studies of the Black Sea*. Sevastopol: MHI AS USSR, pp. 25-33 (in Russian).

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

[7] Blatov, A.S. and Ivanov, V.A., eds., 1992. *Hydrology and Hydrodynamics of the Black Sea Shelf Zone (on the Example of the Southern Coast of the Crimea)*. Kiev: Naukova Dumka, 244 p. (in Russian).

[8] Antonov, L.V., 1913. [Currents in the Black Sea near Batum]. In: Main Hydrographic Department, 1913. *Notes on Hydrography*. St. Petersburg: Main Hydrographic Department Publishing. Vol. 36, pp. 259-266 (in Russian).

near the northern coast – works [1–7] [7, 10, 12, 14, 15, 18, 20, 24, 25], near the northeastern coast works [5–7] [8–11, 13, 16, 17, 19, 21–23] and near the eastern coast works [5, 6, 8] were published. We will denote the northern coast of the Black Sea, including Cape Chersonesos, Cape Fiolent, Cape Aya and the Southern Coast of Crimea as the SCC, the water area of which is historically studied by Marine Hydrophysical Institute of RAS. The coastal water area of the North Caucasian shelf is under the research of the Shirshov Institute of Oceanology of RAS and its Southern Branch. The results of these studies, obtained from representative *in situ* data, are used further in the analysis.

From 1948, a complex experiment on the study of water circulation near the coast of the open part of the Black Sea [1] has been carried out at the sea polygon near Cape Kikineiz during a three-year measurement cycle with a set of MHI Lagrangian and Eulerian current meters. The main regional patterns and factors that form currents in the SCC area were singled out. At distances of up to 2 km from the shore and depths up to 70 m, a bimodal distribution of the frequency of occurrence of the alongshore current directions was reliably revealed. A change of the surface current direction occurs very quickly when the direction of the alongshore wind [1] changes. The established alongshore current velocities slowly decrease from the surface to the bottom, maintaining their direction, associated with the direction of the prevailing winds. The current components along the normal to the coast are extremely small and unstable.

The presented conclusions are confirmed by the results of further MHI studies near Cape Kikineiz (the SCC): in [12], quantitative estimates of the influence of the coastline shape, wind field and hydrological structure on the dynamics of coastal waters are given. When analyzing MHI oceanographic database materials for the coastal water area from Cape Sarych to Cape Kikineiz for 1980–1994, a bimodal structure in the directions of the alongshore current of predominantly cyclonic orientation, similar to the Black Sea Rim Current (RC) direction was also identified [18]. Significant scientific results on the dynamics of large-scale waves trapped by the shore, affecting the circulation of coastal waters, were obtained by MHI during a local dynamic experiment near the SCC [14, 15]. Based on the materials of long-term monitoring of currents near Cape Kikineiz, in [7, 25], experimental estimates of the characteristics of a monomodal cyclonic coastal current shearing in depth were obtained.

From 1955, the Southern Branch of the Institute of Oceanology has been studying coastal currents in the northeastern area of the Black Sea by means of moored autonomous buoy stations [16]. From 1976, long-term hourly measurements of currents have been carried out from a stabilized buoy on the shelf in the Gelendzhik area 5 km from the coast at 70 m depth at 10 m horizon for 3 years, at 25 m horizon – for 5.5 years and at 60 m horizon – for 1.6 years [9]. The results of the analysis of these studies are given in a series of works [8–11, 13], the results of studies of the spatiotemporal variability of currents on the northeastern Black Sea shelf for 1997–2001 are given in [16, 17, 19].

The principal regional patterns and factors that form currents near the North Caucasian coast and the SSC are almost identical, which is confirmed by the following conclusions. The current in the coastal zone near the northeastern

Black Sea coast has a nature of reciprocating movements oriented along the general direction of the coastline in the study area. A characteristic feature of the coastal current regime is a pronounced bimodal type of probability distribution of their directions [8–11, 13, 16, 17, 19]. The bimodal nature of the current directions, determined by the direction of the prevailing winds and the coastline position [8, 9], changes rapidly and almost reversibly. It was noted in [10, 13, 16, 17] that coastal anticyclonic eddies make a dominant contribution to the water circulation near the northeastern Black Sea coast and in [21] it was shown that there are chains of both anticyclonic and cyclonic submesoscale eddies on the narrow North Caucasian shelf. Regarding the existence of a monomodal alongshore current near the North Caucasian coast, in [9, 11] it is noted that the translational coastal current acquires the character of cyclonic reciprocating motions with a bimodal type of the direction probability distribution.

In work [9], it is indicated that there are zones of various coastal circulations near the coast, which are most clearly expressed in gulfs and bays. At the same time, near relatively straight coasts, the currents are directed in the same way as in the RC zone. Identification of the monomodal current characteristics in shallow water near the coast is complicated by a number of objective reasons, including the intense hydrodynamic contribution of disturbances in the near-surface and near-bottom boundary layers [25]. In [9] it was noted that the kinetic energy of the average motion of the current is an order of magnitude less than the kinetic energy of its pulsations. In [16] it was shown that in a narrow coastal strip in shallow water, the frequency of currents in two opposite directions is close to equiprobable at very low values of the mean water transport. The possibility of studying small residual currents, as a rule, is limited by the methodological and instrumental errors of meters, which are especially significant for oceanographic mooring. To obtain reliable characteristics of small residual currents, taking into account the contribution of intense disturbances, an information technology for monitoring currents by a cluster of domestic Eulerian meters was developed and used in MHI [24, 25].

The observations are carried out at the MHI Black Sea Hydrophysical Sub-Satellite Polygon, which is a regionally adapted system for contact monitoring of the natural environment characteristics in the boundary land-sea zone near the SCC, located near a relatively straight section [6, 7]. Instrumental measurements of the characteristics of the coastal ecotone currents are carried out by a cluster of current meters from the pile foundation of the stationary oceanographic platform in the Goluboi Gulf near Cape Kikineiz at a distance of ~ 0.5 km from the coast from November 2001 until present [7, 25]. The current meters at hydrological horizons of 5, 10, 15, 20 and 25 m at the 28 m depth register vector-averaged over a time interval of 5 min every second readings of the vector projection values. Over the 20-year monitoring period (2002–2021), from the initial 5-minute realizations for each measuring horizon, basic series of currents, consisting of 175,320 pairs of hourly mean readings of the vector components, were formed. The operational technological quality control of

[9] Lapin, M.N., ed., 1954. *Pilot of the Black Sea*. Leningrad: Hydrographic Department of the Naval Forces Publishing, 506 p. (in Russian).

measurements ensures metrological unity observance in long-term measurements of the characteristics of coastal currents and the achievement of maximum accuracy of measurements of the averaged current vector components. The measurement velocity module error is 0.1 cm/s, the direction of the current is 3° [24].

The circulation regime of the coastal Black Sea waters is statistically reliably characterized by the phenomenon of a bimodal distribution of the direction frequency, in which the alongshore current has two most probable directions in diametrically opposite angular sectors. For the Black Sea, the main current mode has a cyclonic orientation relative to the deep sea, and the reverse mode has a diametrically opposite direction of the current. For different regions and sections of the coastal water area, the ratios of the contribution between the modes are different. The work [20] presents a review and generalization of materials on various bimodal current structures identified near the Black Sea coast. The existence of a bimodal structure near the coast in some cases is explained by the influence of local wind conditions, and in a number of others, by the hydrodynamic contribution of various anticyclonic eddy formations that have different time scales of existence. Note that these studies were carried out under various physical-geographical, geomorphological, hydrometeorological and hydrological conditions. For a reasoned discussion of this problem and obtaining new quantitative results, MHI has developed a data processing and analysis technique that allows, based on mathematical statistics methods, to evaluate the characteristics, conditions and duration of the existence of the bimodal coastal current structure phenomena under various natural conditions.

The probability density distribution functions (histograms) of the current velocity and direction module contain the necessary statistical material for quantitative estimates of the main and reverse oscillation mode contribution to the coastal current structure. The structure of the stationary bimodal frequency distribution of coastal current components allows consistent development of the necessary set of histograms for the stage-by-stage calculation of integral indicators characterizing the dynamics of the periodic oscillation contribution to the bimodal distribution formation. Each set of histograms of the distribution of current directions was calculated in angular segments of 3°, the velocity module, in 1 cm/s intervals, from chronological series obtained at specified time intervals (periods) of vector averaging, for example, from 5-minute or hourly average readings. Based on the result of summing the current values of the histogram probabilities in the angular sector ±90° from the maximum value of the reverse mode direction probability, the value of the integral probability index of the reverse mode contribution for a specific averaging period is calculated. Integral probability indicators calculated from histograms from 5-minute and mean hourly realizations can differ significantly. According to the hourly data-averaging algorithm, the oscillations with periods of up to 60 minutes are excluded from the time series, as their presence can statistically contribute to the specified integral indicator.

The original field data processing technique was developed based on the combined application of standard digital filtering methods and mathematical statistics. The processing starts with the operations of calculating primary histograms and initial indicators of the integral probability of the reverse mode contribution to the bimodal structure of coastal current directions. This is followed by the procedure of vector averaging of the initial implementations, i.e. elimination of a given time period of oscillations (selective filtering) using the moving mean algorithm when choosing a step with an initial averaging parameter of 1 h. Then, the histograms of these averaged series are calculated and the current indicator of the integral probability of the inverse mode contribution for every horizon. The procedure for successive filtering of the series data is carried out with a step-by-step increase in the averaging period and a constant preservation of the base number of mean hourly readings of the series. As a result of these successive operations, the value of the index of the integral probability of the inverse mode contribution is gradually reduced, and at the final step of averaging after statistical processing, the final value of the index becomes identically equal to zero. The absence of the integral contribution of the reverse oscillation mode is a reliable sign of the existence in the final averaged temporal realization only of the monomodal current and its oscillations.

Further, for each hydrological horizon, from successive sets of stepwise calculated statistical characteristics, the final functions of the distribution index of the integral probability of the reverse oscillation mode contribution, which fall to zero values in the range of selected time periods (frequencies) of oscillations, are formed. When normalization operations and subsequent differentiation are carried out, these functions are transformed into histograms of the distribution of the normalized density of the integral probability of the inverse oscillation mode contribution. The analysis of the results obtained by the original method permits to quantify the role of the regime characteristics variability of the monomodal coastal current in the formation of conditions for the occurrence and duration of the existence of the bimodal structure phenomenon of current directions near Cape Kikineiz.

Results and discussion

The MHI Black Sea Hydrophysical Sub-Satellite Polygon is located on a relatively straight section of the coast of the northern Black Sea in the coastal zone near Cape Kikineiz [4]. The Goluboi Gulf, where a stationary oceanographic platform with a cluster of current meters is located, has a smooth coast outline and relatively shallowly protrudes into the land [12]. The considered polygon area bottom topography towards the open sea along the normal to the coast is characterized by a relatively narrow strip of the shelf and a rapid increase in depths on the continental slope. At the boundary between the shelf and the continental slope, there is a band of increased horizontal velocity gradient of the RC jet, where there is a slight subsidence of waters due to the RC transverse helical circulation. Based on this feature, the RC is separated from the currents of the coastal-shelf zone.

Three separate zones are distinguished near the deep coast [12]: zone of the RC main jet; current on the shelf and current in the coastal strip. The RC main jet zone is located on the continental slope, where in the midstream the current has a monomodal probabilistic histogram reflecting predominantly unidirectional cyclonic water transport, and the current velocity is modulated by orbital velocities of different-scale eddy, wave and other hydrodynamic disturbances [5, 6] [10, 13, 16, 17, 20]. The current in the shelf zone is often considered as the RC periphery, where the main mode current recurrence decreases towards the coast and the elliptical form of the orbital alongshore water circulation is transformed. In the probability histograms of the current direction, a bimodal nature of the distribution is manifested with varying contribution ratios between modes [6, 7] [13–17, 20].

The subject of this research is the features of the water circulation formation in the coastal strip up to 0.5 km wide near the coast, i.e., in the shallow water area of the coastal ecotone near the SCC. In all publications on the research problem, it is stated that in the coastal zone, alongshore currents have the character of reciprocating movements, and the water circulation regime is statistically reliably characterized by a bimodal distribution of direction frequency. The possibility of the stationary monomodal current existence near the coast has not been discussed in most publications. Based on the results of the analysis of materials of long-term current monitoring in the Black Sea Hydrophysical Sub-Satellite Polygon area near the northern Black Sea coast, for the first time in the practice of a full-scale experiment, the fact of existence was reliably revealed and the quantitative regime characteristics of a stationary monomodal along-the-depth sheared coastal current were determined [7, 25]. When the current is perturbed, the wave and eddy orbital motions of water near the coast are transformed into a system of reciprocating alongshore oscillations, which are practically collinear with the monomodal current.

When analyzing the statistical and spectral processing results, it was found that there are two regimes of water circulation near the SCC – the regime of stationary monomodal alongshore current and the regime of bimodal modulation of the total alongshore current direction by intense hydrodynamic disturbances. In the monomodal regime, the current velocity module dominates over the orbital velocity module of the collinear hydrodynamic perturbation, and periodic oscillations of only the velocity of the total alongshore current occur without inversion of its direction. The bimodal structure of the total alongshore current arises and exists in situations where the orbital velocity module of the collinear oscillation in antiphase exceeds the unimodal current velocity module. In this case, various bimodal structures with inverse oscillations in both direction and velocity of the total alongshore current are formed.

To estimate the trend in the interannual variability of the coastal water circulation, the calculation of the mean annual and average long-term characteristics of the vertical structure of the monomodal along-the-depth sheared coastal current was carried out. The results of calculating the averages for the 20-year monitoring period (2002–2021) and the annual averages for 2020 and 2021 values of the velocity module and current direction at the 5, 10, 15 and 20 m hydrological horizons are given in the Table. The values of the mean long-term regime characteristics of the monomodal coastal current at all horizons over the 20-year period did not change compared to the previous estimation period [25]. The values of the mean annual current velocity at all horizons in relation to the mean annual velocity only in 2020 anomalously decreased by 30%. The root-mean-square deviations of the mean annual velocities from the long-term averages at all horizons for the previous 18 years and the subsequent 2021 did not exceed 10%. The reliable fact of the anomalous decrease in the average annual current velocity was further used in estimation of the role and change in the indicator of the contribution of interannual variability to the formation of the bimodal structure of coastal water circulation directions.

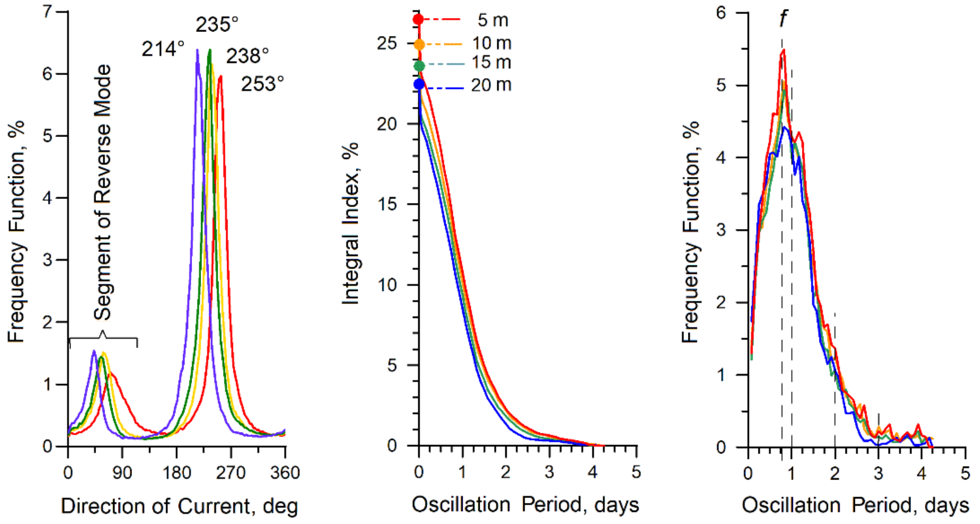
To estimate the energy characteristics of the temporal variability of the coastal current oscillations at the 5, 10, 15 and 20 m horizons and the distribution spectra of the kinetic energy density were calculated. Intense oscillations of the coastal current are reliably distinguished in the inertial-gravitational (near the local inertial 17.1 h and daily periods), subinertial (at periods of ~ 6 and 12 days) and seasonal ranges of variability. The results of the spectral calculations carried out are similar to those published in [25]. The spectral features of the kinetic energy density distributions in the gravitational oscillation range of 10 min – 1 h are similar to the features of the energy spectra of vertical displacements of the thermocline during short-period internal waves in the SCC zone [23]. However, the results of studies of short-period oscillation variability of coastal currents are not considered in this paper.

Variability of mode characteristics of the depth-sheared monomodal coastal current

Depth, m	Velocity, cm/s	Direction, °	Velocity, cm/s	Direction, °	Velocity, cm/s	Direction, °
	2002–2021		2020		2021	
5	8.1	253	5.7	255	8.3	262
10	8.0	240	5.8	241	8.2	248
15	7.7	234	5.7	235	7.8	236
20	7.0	217	5.2	217	7.0	215

To solve the tasks at the initial stage of processing, calculations of histograms and initial indicators of the integral probability of the inverse mode (hereinafter – the integral indicator) contribution at each horizon were carried out. Fig. 1, *a* shows the empirical distribution functions of the probability density of the occurrence frequency of alongshore water circulation directions, calculated from ~ 2 million pairs of initial vector-averaged over a time interval of 5 min components of the current vector in 3° angular segments for each measuring horizon. The analyzed range of the reverse mode of oscillations with diametrically opposite directions with respect to the directions of main mode oscillations is also indicated here. The calculated initial integral indicators have a maximum value of 26.5% at 5 m horizon, which steadily decreases to 22.5% towards 20 m horizon.

In Fig. 1, *b*, the values of the initial integral indicators for each horizon are marked by the corresponding circles. These values are initial and are used when normalizing subsequent current values of the integral indicator to estimate their relative changes.



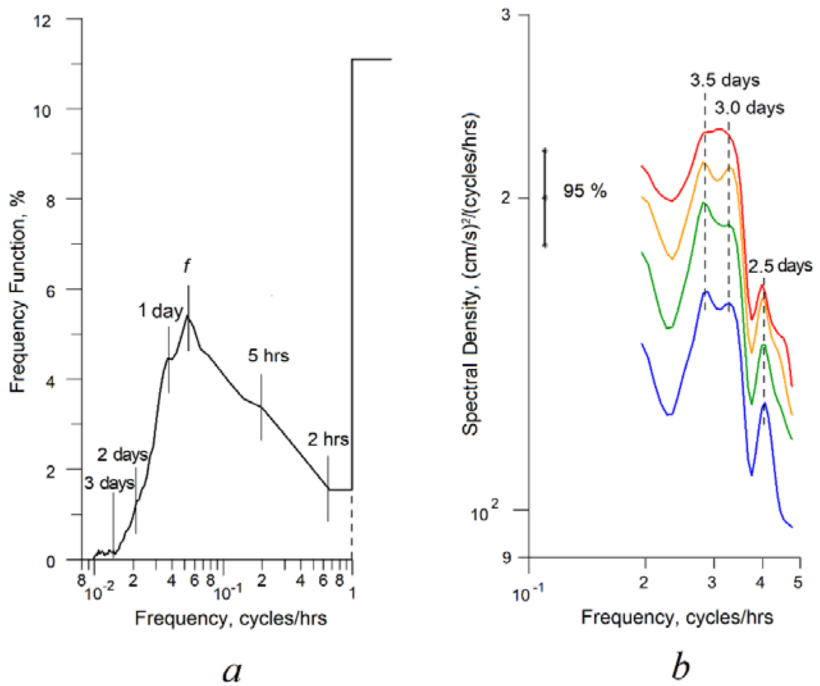
a *b* *c*

F i g. 1. Empirical functions of: *a* – the probability density of the alongcoastal water circulation directions; *b* – the probability of exceeding the contribution of the reverse oscillation mode; *c* – the normalized density of probability of the contribution of reverse oscillation mode at the horizons 5, 10, 15, and 20 m (red, orange, green and blue lines, respectively); *f* is the local inertial frequency

According to the method developed, the data of the vector base of mean hourly series of currents, which have passed the state registration, have been sequentially processed [25]. To calculate the histograms and the current integral indicators of the contribution of the reverse mode, realizations from 175,320 pairs of hourly average readings of the current vector components, as well as additional data necessary for averaging, were used. The values of the integral indicators of mean hourly data obtained by averaging from 5-minute series decreased to 23.5% at 5-m horizon and to 20.5% at 20-m horizon. As a result of filtering, the relative decrease by ~ 11.5% of the normalized integral indicator at 5 m horizon is due to the partial elimination of the reverse mode contribution with a corresponding increase in the fundamental mode contribution.

The operations of selective filtering of vector series were carried out with a successive increase in the filter parameter by 1 hour, with the corresponding calculations of histograms and current integral indicators. At the end of processing, the final distribution functions of the indicator of the integral probability of the reverse oscillation mode contribution for each horizon were formed. For processing and analysis, two sets of realizations were used: the first one was formed without anomalous 2020 data, the second one, with a full set of data. Fig. 1, *b* shows histograms of the evolution of the integral indicator distribution at 5, 10, 15 and 20 m horizons for the first set of realizations. The contribution of the reverse oscillation mode as a result of filtering was completely eliminated in time realizations almost simultaneously at all horizons with a final averaging period of 4.25 days (102 h).

To identify the features of the integral indicator distribution at different horizons, the histograms were normalized to their maximum initial value for 5 m horizon and the first differences in mean hourly realizations were calculated. As a result, for each horizon, the histograms of the distribution of the normalized density of the integral probability of the reverse oscillation mode contribution to the formation of the bimodal structure of current directions were formed (Fig. 1, *c*). The values of the normalized density of the integrated probability in 5 min – 1 h oscillation range at the initial processing step, for example, for 5 m horizon, reached ~ 11.5%; in Fig. 1, *c*, they are not shown as they coincide with the corresponding axis of the probability density graph. The integral contribution of this oscillation range is shown in Fig. 2, *a*. The distributions in Fig. 1, *c* demonstrate the features of the contribution of coastal current oscillations in 1 h – 5-day period range. For the first set of realizations, the upper limit of this range at all horizons is limited by a period of 4.25 days. Obviously, the dominant reverse mode contribution is made by oscillations with periods of up to 2 days, with the maximum contribution of oscillations in the range of inertial and diurnal periods and a decrease in the intensity of oscillations with depth.



F i g. 2. Function of the normalized density distribution of integral probability of the reverse oscillation mode contribution (averaged over the 5–20 m layer) (*a*) and the spectra of distribution of the kinetic energy density of the coastal current oscillations within the range of periods from 2 to 5 days at the horizons 5, 10, 15, and 20 m (red, orange, green, and blue lines, respectively) at the 95% confidence interval (*b*)

To quantify the contribution of these oscillations, the distribution histograms of the integral indicator were normalized to its maximum initial values for each horizon. The generated histograms of the distribution of the normalized density of the integral probability of the reverse mode contribution have close values and are averaged in 5–20 m layer. Fig. 2, *a* shows an averaged empirical distribution function of the normalized density of the reverse oscillation mode contribution in the range of 1 h – 5-day periods.

Outside the main range, the level of the normalized density of the integral probability of the gravity range oscillation contribution of 5 min – 1 h, averaged over 5–20 m layer, corresponding to ~ 11% is shown in Fig. 2, *a*.

According to the analysis of the results obtained from calculations for the first set of realizations, the reverse oscillation mode formation near Cape Kikineiz is quantitatively contributed by current oscillations in the following time ranges of variability: 5 min – 1 h with a contribution of ~ 11%; 1 h – 2 days ~ 80%; 2–3 days ~ 7%; 3–4 days ~ 2%. The total contribution of up to 91% to the reverse mode formation is made by coastal current oscillations at periods of up to 2 days and 9% at periods of 2–4 days.

The processing results of the second set of realizations for 10, 15 and 20 m horizons coincide with the results of processing the first one. Significant differences were identified only in the near-surface layer at 5 m horizon, where the final processing period increased to 5 days (122 h). The total contribution of up to 91% to the reverse mode formation is concentrated in oscillations with periods of up to 2 days, and 9% of the contribution is dispersed in the range of periods of 2–5 days.

Thus, significant interannual differences in the mean annual regime characteristics of the unimodal current can affect the structure of formation characteristics and the duration of the existence of the bimodal structure phenomenon of coastal water circulation directions.

According to the distribution function (Fig. 2, *a*), a significant contribution to the bimodal structure formation is made by oscillations in the inertial-gravitational range of coastal water circulation variability. The studies of oscillations in the SCC shelf waters in this variability range, including oscillations in daily, local inertial periods and short-period internal waves, are constantly being improved [5-7] [6, 12, 20, 22, 23] due to the outstanding role of these oscillations in tide-free Black Sea water dynamics. At the same time, for the water area near the SCC, it is also necessary to take into account the contribution of trapped waves generated by local winds with a period of ~ 26.5 h [15], as well as seiches [12].

It was shown in [10, 13, 16, 17] that mesoscale anticyclonic eddies with 2–7-day duration make a significant contribution to the bimodal regime of current on the shelf near the northeastern coast of the Black Sea. In [21] it was noted that on the North Caucasian shelf there are chains of not only anticyclonic, but also cyclonic submesoscale eddies. According to the distribution (Fig. 2, *a*), oscillations in the range of 2 –5-day periods also contribute to the formation of the bimodal regime of the coastal current near Cape Kikineiz. In this case, the contribution of 2-day period oscillations is an order of magnitude higher than those with 2–5-day periods.

To obtain additional information about the features of the current variability near the SCC in the range of 2–5-day periods, the long-term mean distribution spectra of the kinetic energy density of oscillations were calculated (Fig. 2, *b*). At all measurement horizons, the spectral maxima of coastal current oscillations in the range of periods of 3.0–3.5 days significantly exceed the 95% confidence interval with a decrease in oscillations near periods of ~ 4.3 days. According to the materials of the review of publications [5] [12], in the SCC region, the reliable fact of the serial generation of inertial oscillations with the duration of each series of inertial gyres for 3–4 days should also be taken into account.

This paper presents materials that allow to expand scientific understanding of the formation features of alongshore circulation of the coastal ecotone near the SCC and the essence of the phenomenon of the bimodal structure of coastal current directions. At the same time, it is necessary to continue further studies of the SCC water dynamics as a necessary element for the formation and development of regional structure of ecological and economic monitoring of the coastal ecotone [1].

Conclusion

An original technique for processing and analyzing the *in situ* data based on the combined application of standard digital filtering methods and mathematical statistics in the study of the features of coastal ecotone water circulation formation near the SCC has been developed and put into practice. The results of calculations using the developed method and the data of 20-year monitoring of the monomodal coastal current variability near Cape Kikineiz for 2002–2021 made it possible to quantify the contribution of intense current oscillations to the formation of the phenomenon of the bimodal structure of coastal water circulation.

New scientific results are obtained based on processing and analysis of a full set of the *in situ* data, taking into account systematization of previously published results on the problem considered. It is shown that, depending on the hydrodynamic conditions near the SCC, there are two regimes of coastal water circulation – the regime of monomodal alongshore current and the regime of bimodal modulation of the alongshore current direction under intense hydrodynamic disturbances. The bimodal structure of the total alongshore current arises and exists in situations where the orbital velocity module of the collinear oscillation in antiphase exceeds the modulus of the monomodal current velocity. In this case, various bimodal structures with inverse oscillations in both direction and flow velocity are formed. During the formation of the reverse mode of the bimodal structure near Cape Kikineiz, the dominant contribution of oscillations in the inertial-gravitational variability range was identified at all horizons.

Some prospects for the development of studies of the coastal water circulation as an essential natural factor influencing the socio-economic development of the SCC region during the formation of the structure of ecological and economic monitoring of coastal ecotone waters are shown.

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