Original article

Peculiarities of Interseasonal Variability of Alongshore Wind Circulation and Coastal Currents off the Southern Coast of Crimea

A. S. Kuznetsov

Marine Hydrophysical Institute of RAS, Sevastopol, Russia
e-mail: kuznetsov_as@mhi-ras.ru

Abstract
The paper analyses decade-average (2013–2022) statistical and spectral characteristics of mesoscale and synoptic variability of the wind field for the atmosphere surface layer and the surface current to reveal regularities and peculiarities of the wind variability and quasi-stationary alongshore current near Cape Kikineiz of the Southern Coast of Crimea. Complex instrumental monitoring was carried out under open sea conditions using clusters of hydrometeorological and oceanological meters at the stationary oceanographic platform of the Black Sea hydrophysical sub-satellite testing area of Marine Hydrophysical Institute of RAS. The author used a dataset of chronological sequences of mean-hourly vector-averaged data for May–October and November–April half-year periods to quantify the values and identify trends in the interseasonal variability of wind and current field characteristics. During the selected time periods, clear seasonal differences in the thermal structure and dynamics of both the surface wind field and coastal waters were observed near the coast. Based on instrumental monitoring materials, peculiarities of coastal water circulation under seasonal variability of local wind conditions were studied. The spectral analysis results estimate the energy contribution of breeze wind circulation to the seasonal intensification of the mesoscale variability of the alongshore current. During the entire annual cycle, multiscale alongshore reciprocating wind fluctuations, parallel to the Main Ridge of the Crimean Mountains, apart from the background large-scale wind field, were detected at the seacoast. Such wind fluctuations influence the variability of the coastal-waters alongshore circulation, which allows studying the conditions and peculiarities of the bimodal distribution formation of the direction recurrence of the quasi-stationary alongshore current near Cape Kikineiz.

Keywords: Black Sea, Southern Coast of Crimea, coastal zone, instrumental monitoring, local wind field, alongshore current, energy spectrum

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Особенности межсезонной изменчивости вдольбереговой циркуляции ветра и прибрежного течения у Южного берега Крыма

А. С. Кузнецов

Морской гидрофизический институт РАН, Севастополь, Россия
e-mail: kuznetsov_as@mhi-ras.ru

Аннотация
По результатам анализа средних за десятилетие 2013–2022 гг. статистических и спектральных характеристик мезомасштабной и синоптической изменчивости поля ветра приводного слоя атмосферы и приповерхностного течения выделены закономерности и особенности изменчивости ветра и квазистационарного вдольберегового течения у м. Кикинеиз Южного берега Крыма. Комплексный инструментальный мониторинг выполнен кластерами гидрометеорологических и океанологических измерителей в условиях открытого моря со стационарной океанографической платформы Черноморского гидрофизического подспутникового полигона Морского гидрофизического института РАН. Для количественных оценок значений и выявления тенденций в межсезонной изменчивости характеристик поля ветра и течения использован набор хронологических последовательностей среднечасовых векторно-осредненных данных за полугодия май – октябрь и ноябрь – апрель. В выделенные временные периоды у побережья наблюдались явные сезонные различия в термической структуре и динамике как приповерхностного поля ветра, так и прибрежных вод. На основе материалов инструментального мониторинга исследованы особенности циркуляции прибрежных вод при сезонной изменчивости местных ветровых условий. По результатам спектрального анализа получены оценки энергетического вклада бризовой циркуляции ветра в период сезонной интенсификации мезомасштабной изменчивости вдольберегового течения. В течение всего годового цикла у побережья в море наряду с фоновым крупномасштабным полем ветра выявлены разномасштабные вдольбереговые возвратно-поступательные колебания ветра, ориентированные параллельно хребту Главной гряды Крымских гор. Такие колебания ветра влияют на изменчивость вдольбереговой циркуляции прибрежных вод, что позволяет исследовать условия и особенности формирования бимодального распределения повторяемости направления квазистационарного вдольберегового течения у м. Кикинеиз.

Ключевые слова: Черное море, Южный берег Крыма, прибрежная зона, инструментальный мониторинг, поле местного ветра, вдольбереговое течение, энергетический спектр

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Introduction

Research into the causes of intense variability of currents off the coast of Crimea is due to the need for reliable navigation support for maritime transport, as well as the extraction and reproduction of resources in the Black Sea coastal zone. The sphere of recreational services and the construction of housing and utility complexes are intensively developing at the Southern Coast of Crimea (SCC), and a network of port, hydraulic engineering and treatment facilities with sewer collectors for the bottom discharge of industrial wastewater from land into the coastal zone of the sea has been formed in the zone of interface between land and sea.

Under such conditions, the preservation of the SCC natural ecosystem depends on the balanced consumption and reproduction of natural resources while limiting the flow of pollution into the sea during waste disposal. The existence and sustainable economic development of such a social eco-economic system is possible only with rational management of environmental activities and effective quality control of the marine environment [1].

Specific structure of the transport of coastal waters and contaminants off the coast of Crimea is a natural factor that invariably minimizes the consequences of technogenic and anthropogenic loads on the marine environment. Long-term instrumental monitoring of the dynamics of coastal waters carried out by Marine Hydrophysical Institute (MHI) at the Black Sea hydrophysical sub-satellite testing area (BSHSTA) near Cape Kikineiz makes it possible to estimate the impact of changes in natural, climatic and anthropogenic factors on the state of the coastal ecosystem reliably.

This work is aimed at obtaining new scientific knowledge about the peculiarities of interseasonal variability of alongshore wind circulation and coastal currents based on the results of statistical and spectral analysis of the 2013–2022 instrumental monitoring data.

Materials and methods of study

Since 1929, a system of hydrometeorological and oceanographic observations has been in operation and is constantly being improved at the BSHSTA of MHI in the settlement of Katsiveli located near Cape Kikineiz [2]. Instrumental monitoring of the characteristics of the coastal waters is carried out by hydrometeorological and oceanological meters from an oceanographic platform located in the open sea at a distance of ~500 m from the coast.

The wind field characteristics are studied using data from a set of automated hydrometeorological complexes with primary measuring transducers of wind indicator M-63 and IPV-M as part of complex MGI-6503 [2] and small-sized wind sensors (DVM) as part of the hydrometeorological data collection complex (KSGD) [3] installed compactly at a height of 18 m above sea level on the oceanographic platform communication mast. The complexes operate in a second-by-second measurement mode with a nominal sensitivity of the wind speed module measuring channel of no more than 0.1 m/s and wind direction channel of no more than 3°. A vector-averaged series of 87,648 pairs of mean-hourly samples of vector components was formed for the 2013–2022 monitoring period.

Data from current meters MGI-1308 [2, 4] are used on hydrological horizons from the surface layer to the bottom one at a depth of ~28 m to study the circulation of coastal waters. The meters record vector-averaged second-by-second readings of the speed and direction of the current vector over a time interval of 5 minutes with a nominal sensitivity of the speed module measuring channel of 0.1 cm/s and a current direction channel of 3°. Basic vector-averaged series of 87,648 pairs of mean-hourly readings of the current vector components were formed for each 5, 10, 15, 20 m measuring horizon over the 10-year period specified above.

Primary measuring transducers of the complexes undergo metrological certification in the MHI metrology and standardization service in the prescribed manner. Further operational technological quality control of measurements ensures compliance with metrological unity during long-term measurements of the characteristics of coastal currents and wind, thus eliminating the impact of faulty values and significant methodological measurement errors. Further averaging of data processing results makes it possible to increase the accuracy of statistically mean values of both current and wind to the level of maximum random errors limited by the resolution (nominal sensitivity) of corresponding primary measuring transducers of the complexes.

Scientific novelty of the set of the 2013–2022 systematized materials used in this work is proved by certificates of state registration [1), 2), 3)]. Materials from vector databases of synchronous monitoring of the coastal current and wind of the atmosphere surface layer were used in statistical and spectral analysis. The intensity and spatiotemporal peculiarities of the dynamics of water and wind near the SCC were studied based on the obtained quantitative estimates. Spectral analysis of the variability of the energy intensity of current and wind fluctuations was carried out under a linear estimate of the spectrum through smoothing of periodograms using a processing program developed by MHI based on work [4)] and applied in [4–6].

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1) Kuznetsov, A.S. and Zima, V.V., 2019. *Database for Monitoring the Dynamics of the Black Sea Coastal Currents near the Southern Coast of Crimea for 2008–2015 According to Measurements on a Stationary Oceanographic Platform near Cape Kikineiz* [Database]. Moscow. State Registration No. 2019620377 (in Russian).

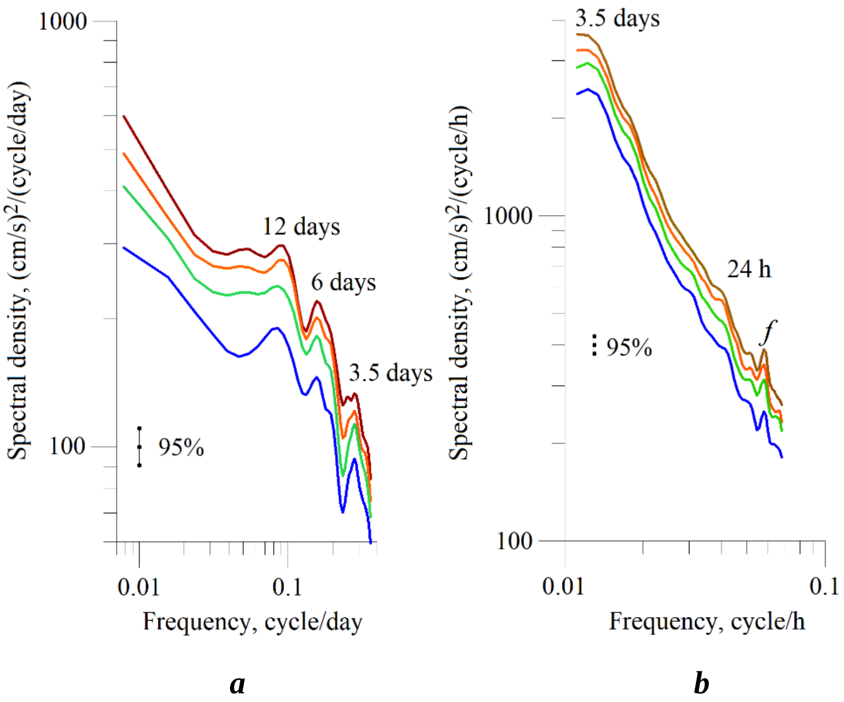
2) Kuznetsov, A.S. and Zima, V.V., 2020. *Database for Monitoring the Current Field of the Coastal Zone of the Black Sea near the Southern Coast of Crimea for 2016–2019* [Database]. Moscow. State Registration No. 2020621445 (in Russian).

3) Kuznetsov, A.S., Garmashov, A.V. and Zima, V.V., 2023. *Database for Wind Characteristics Monitoring for the Black Sea Coastal Ecotone at Cape Kikineiz of the Southern Coast of Crimea for 2013–2022* [Database]. Moscow. State Registration No. 2023622482 (in Russian).

4) Konyaev, K.V., 1981. [*Spectral Analysis of Random Oceanological Fields*]. Leningrad: Gidrometeoizdat, 207 p. (in Russian).

Results and discussion

As part of monitoring, the problem of estimation of the coastal wind circulation contribution to the formation of the peculiarities of interseasonal variability of the alongshore currents is urgent. According to [4], a quasi-stationary alongshore current is reliably expressed in the coastal zone near Cape Kikineiz and the main modes of its variability have been studied. As noted in [7], the spatial peculiarities of water dynamics near the coast are determined by the configuration of the coastline and the bottom topography. Work [4] presents the results of studies of the main axis orientation of wave-vortex elliptical orbital water movements transformed near the coast. In general, the directions of such reciprocating fluctuations are oriented along the direction of the current which is oriented along the corresponding isobath of the bottom topography at a specific measuring horizon [8]. The 2013–2022 average speed of the alongshore quasi-stationary current is 7.9 cm/s in a west-southwest direction (253°) in the sea surface layer at a horizon of 5 m and 6.7 cm/s in a direction of 215° in the bottom layer at a horizon of 20 m. Figure 1 shows the 2013–



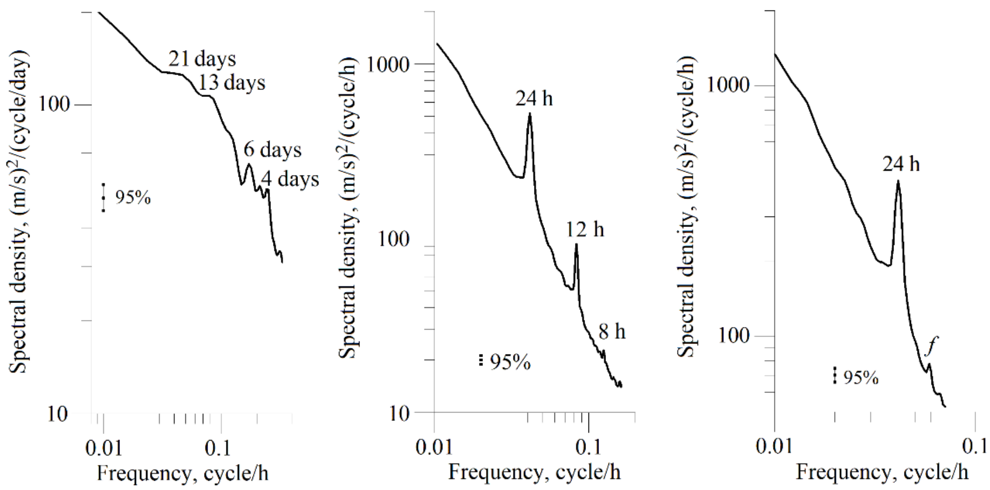
F i g . 1 . Full energy spectra of coastal current fluctuations near the Southern Coast of Crimea at 5, 10, 15, 20 m hydrological horizons (brown, orange, green, blue lines, respectively) at 95% confidence interval in the range of periods: 3–128 days (*a*); 14–96 h (*b*); *f* is local inertial frequency

2022 average energy spectra of coastal current fluctuations at hydrological horizons in the range of periods 3–128 days (Fig. 1, *a*) and 14–96 h (Fig. 1, *b*), similar to the results obtained earlier [4, 5].

It is noted in [7] that the variability of wind conditions near the SCC causes rapid restructuring of coastal currents. Next, we consider the results of wind conditions regime and variability analysis obtained from the 2013–2022 instrumental monitoring materials, which are necessary for further discussion.

Peculiarities of mean long-term wind variability. The total wind field of the Black Sea region is formed by the background wind and the superposition of local winds of thermal and orographic origin which play a significant role in the formation of the atmosphere surface layer wind field [7, 9, 10]. This instrumental monitoring made it possible to identify reliably and specify the spectral composition of wind field fluctuations near the SCC. Fig. 2 shows the 2013–2022 average energy spectra of wind variability in the atmosphere surface layer in the range of periods 3–128 days (Fig. 2, *a*), 6–96 h (Fig. 2, *b*) and 14–96 h (Fig. 2, *c*).

Fig. 2, *a* shows the energy spectrum of wind fluctuations in the range of mesoscale and synoptic variability where spectral peaks are reliably identified at periods of about 4 and 6 days and the intensification of synoptic wind fluctuations is expressed at periods of 8, 13 and 21 days.



a ***b*** ***c***

F i g . 2 . Full energy spectrum of wind variability in the atmosphere surface layer in the coastal marine ecotone zone near the Southern Coast of Crimea at 95% confidence interval in the range of periods: 3–128 days (*a*); 6–96 h (*b*), 14–96 h (*c*), where *f* is local inertial frequency

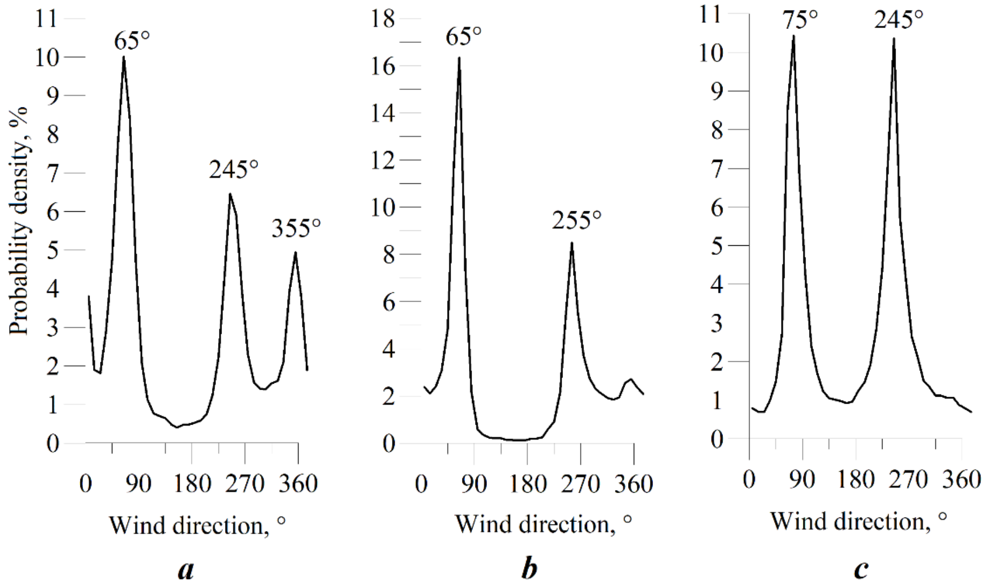
It is noted in [9] that the orographic effect should consist in the generation of stationary inertia-gravity waves trapped by the surface when the wind flows around the mountainous relief surrounding the Black Sea. According to the results of numerical modelling [10–12] and analysis of *in situ* data [6], local breezes and mountain slope winds have a pronounced daily periodicity. Figure 2, *b* shows the energy spectrum of wind fluctuations containing spectral maxima of wind fluctuations at periods of about 8, 12 and 24 h.

In order to isolate inertial wind fluctuations in the presence of intense intraday fluctuations, the contribution of gravitational fluctuations with periods of less than 14 h was removed from the initial data by digital filtering. Figure 2, *c* shows the energy spectrum of wind fluctuations calculated in the range of periods of 14–96 h where the spectral peak of wind fluctuations with a period of ~ 17 h (local inertial frequency) was reliably identified.

Peculiarities of the wind field spatial orientation. According to the results obtained, peculiarities of the spatial orientation of the total wind field main components in the region were identified in the atmosphere surface layer. Figure 3, *a* shows empirical probability density function of the distribution of wind field directions calculated in angular segments ±5° for 2013–2022. Three main directions of air masses movement in the atmosphere surface layer near Cape Kikineiz were identified. The winds of the alongshore east-northeast (~ 65°) and west-southwest (~ 245°) points are almost collinear and parallel to the Main Ridge range of the Crimean Mountains in the region, and the wind of the northern (~ 355°) points is directed downslope towards the sea normal to the mountain range.

Alongshore air flows can be periodically formed owing to certain natural conditions near the SCC and disturbances introduced by the Crimean Mountains into the background wind speed fields, and a zone of mesoscale wind speed fluctuations is created in such a way [12].

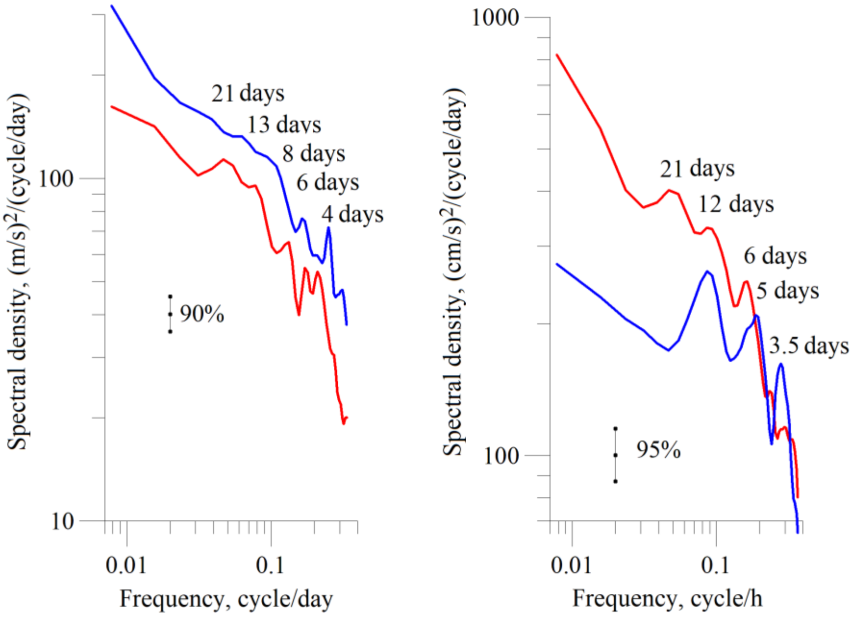
Figure 3, *b* shows empirical probability density function of wind directions calcu-lated after removing the contribution of inertia-gravitaty and daily wind variability from the initial data by digital filtering. After filtering, the alongshore directions of the reverse movement of air masses parallel to the mountain range are preserved, but at the same time the contribution of the wind from the northern directions is radically transformed. Figure 3, *c* shows empirical probability density function of wind directions, calculated after removing the contribution of inertia-gravity, daily fluctuations and large-scale background wind from the initial data. The background wind of north-northeast (~ 25°) points with a speed module of 1.5–1.6 m/s was calculated for a 10-year monitoring period. Upon completion of the processing, the contribution of wind fluctuations along the coastal points is reliably identified, but the wind of the northern points is not self-identified (Fig. 3, *c*). As a result, it was established that alongshore fluctuations of the coastal wind of various time scales dominate annually in the atmosphere surface layer at a distance of ~ 500 m from the coast with the contribution of local and regional background wind.



F i g . 3 . Empirical probability density distribution function for wind directions in the atmosphere surface layer: *a* – based on the initial data; *b* – after removing the contribution of inertia-gravity and daily wind variability from the initial data; *c* – after removing the contribution of inertia-gravity, daily and large-scale background wind variability from the initial data

Data from the surface horizon of 5 m only were used to compare the statistical and spectral characteristics of wind variability in the atmosphere surface layer and corresponding variability of the coastal current in the upper active layer of the sea. Two separate sets of mean-hourly data were generated for May–October (half-year I) and November–April (half-year II) to calculate the characteristics of both wind and current for 2013–2022. It should be noted that chronological data sets for the indicated half-years are also used when numerically modelling the Crimean region wind regime, its seasonal variability and breeze circulation peculiarities [10, 11].

Interseasonal peculiarities of large-scale wind and current variability. Figure 4 shows full energy spectra of variability of winds in the atmosphere surface layer (Fig. 4, *a*) and currents in the sea surface layer (Fig. 4, *b*) calculated for half-years I and II in the range of periods 3–128 days. In Fig. 4, *a*, spectral peaks of wind fluctuations were reliably identified at periods of 5–6 days, 8, 13 and 21 days in half-years I, and in half-years II, a peak was reliably identified at a period of 4 days and intensification of synoptic wind fluctuations was noted in the range of periods of 8–21 days compared to spectrum calculated for half-years I. In Fig. 4, *b*, spectral peaks



a ***b***

F i g . 4 . Full energy spectra of long-wave fluctuations in the range of periods 3–128 days: *a* – winds in the atmosphere surface layer; *b* – currents in the sea surface layer, calculated for the half-year periods May–October and November–April 2013–2022 (red and blue lines, respectively)

of long-wave current fluctuations were reliably identified at periods of ~3.5, 6, 12 and 21 days calculated for half-years I and at periods of ~3.5, 5 and 12 days for half-years II. These long-wave movements propagate along with the alongshore current leaving the coast on the right-hand side.

Research of interseasonal differences in the spectral composition of long-wave fluctuations in the coastal current is possible as part of *in situ* and numerical model studies of long-wave motions including coastal trapped waves [5)]. Work [4] presents review of the results obtained earlier in studies of long-wave movements near the SCC which determine trapping and accumulation of wave energy, meandering of currents and formation of mesoscale eddy structures.

Coastal trapped waves are known to be mainly generated by alongshore wind stress fluctuations. According to Fig. 4, *c*, such wind fluctuations are reliably present near the SCC, and the spatiotemporal characteristics of coastal trapped waves

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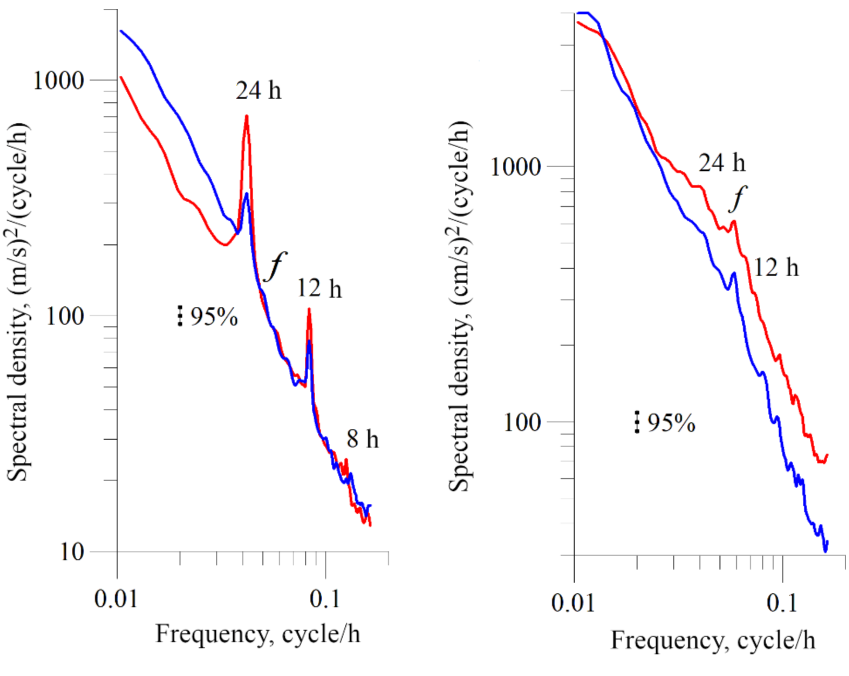
[5)] Ivanov, V.A. and Yankovsky, A.E., 1992. [*Long-Wave Motions in the Black Sea*]. Kyiv: Naukova Dumka, 110 p. (in Russian).

are determined by the scale of forcing atmosphere influences in the region [13]. Long-wave current fluctuations with a period of about 6 days in summer are caused by the Black Sea surge circulation with a periodicity of 5–7 days, and fluctuations with a period of about 12 days were previously identified as long coastal trapped waves and generated by remote wind action [13]. Energy spectra in the mesoscale and synoptic range of variability calculated from synchronous cur-rent and wind data have similar spectral ranges of the intensification of fluctuations. Detailed studies of cause-and-effect statistical relationships among the characteristics of these long-wave fluctuations are planned to be carried out in the future.

Interseasonal peculiarities of inertia-gravity and daily variability of wind and current. Figure 5 shows full energy spectra of inertia-gravity and daily fluctuations of winds in the atmosphere surface layer (Fig. 5, *a*) and currents in the sea surface layer (Fig. 5, *b*) calculated for half-years I and II in the range of periods 6–96 h. In Fig. 5, *a*, energy maxima were reliably identified for a pair of spectra of wind



a ***b***

F i g . 5 . Full energy spectra of inertia-gravity and daily fluctuations in the range of periods 3–128 days: *a* – winds in the atmosphere surface layer; *b* – currents in the sea surface layer calculated for the half-year periods May–October and November–April 2013–2022 (red and blue lines, respectively) fluctuations at periods of 12 and 24 h, as well as fluctuations at local inertial frequency *f* and at a period of 8 h. In Fig. 5, *b*, spectral peaks are reliably identified for a pair of spectra of coastal current fluctuations at local inertial frequency *f*.

In order to assess significance and reliability of the identified spectral maxima of fluctuations of both wind and current in the prescribed manner [4)], corresponding 95% confidence intervals were calculated for an actual number of degrees of freedom of ~ 1600. This allowed evaluation of differences when comparing the spec-tral levels of the formed pairs of spectra with high accuracy.

In Fig. 5, *a*, the mean long-term amplitudes of wind fluctuations in the range of periods of 36–96 h for half-years II exceed the amplitude of corresponding fluctuations for half-years I by ~ 40%. Further along the spectrum, type and compared levels of wind spectra in the range of fluctuations of 6–26.5 h coincide while differing in the values of the levels of spectral maxima at periods of 12 and 24 h. According to the results obtained previously *in situ* [6, 7] and in model [10, 11] experiments, breeze circulation strengthens from May to October causing significant interseasonal differences in the fluctuation intensity for periods of 12 and 24 h (Fig. 5, *a*).

Figure 5, *b* shows the distribution of the current energy spectral density in the surface layer of the sea for half-years I and II with no energy differences in the spectral levels in the range of fluctuations of 36–96 h. Further along the spectrum in the range of fluctuations of 6–36 h, these differences exceed the limits of 95% confidence interval. The mean long-term amplitudes of current fluctuations in the range of periods of 6–36 h for half-years I exceed the amplitudes of fluctuations for half-years II by ~ 25%. Such differences in the inertia-gravity and daily range of current fluctuations occur from May to October in the upper active layer of the Black Sea under conditions of stable thermal (density) stratification of waters [14]. As is known, a field of intense short-period internal waves is formed in the active layer during this period of the year, thus providing energy sink of the current long-wave fluctuations on the Black Sea shelf. *In situ* studies of the dynamics of inertia-gravity and short-period internal waves on the shelf in the Black Sea upper active layer are constantly being improved and new scientific results of such studies are given in [15–17].

It should be noted that the coastal waters off the SCC including the continental shelf with bays and harbours are the marginal part of the Black Sea shelf zone connected to the land. Currently, some researchers believe that the only statistically reliable characteristic of the water circulation regime near the coast is the bimodal distribution of current direction frequency. However, according to the MHI *in situ* results [4], a monomodal alongshore current directed in the same way as the Rim Current was reliably identified near Cape Kikineiz. At the same time, work [5] reveals that the dominant contribution (~ 80%) is made by fluctuations in the inertia-gravity and daily range, whereas 20% of the contribution is distributed in the mesoscale range of current fluctuations with periods up to 4–5 days during the formation of the reverse mode of current direction bimodal distribution near the SCC.

As is known, inertial fluctuations take place in the Black Sea with acting force changes and represent a circular or elliptical anticyclonic rotation of the current speed vector which is radically transformed near the coast. Inertial currents near the coast (quasi-reversible water circulation) are observed near the SCC, usually after the cessation of the long-term alongshore wind, when the inertial current vector rotates clockwise for periods of about 17 h at a spatial scale of the anticyclonic eddy of less than ten kilometers [7]. According to the 2013–2022 monitoring studies, inertial fluctuations of currents near Cape Kikineiz arise regularly and exist in the form of periodic packets, and it is noted in [7] that the duration of a series of such inertial anticyclonic eddies is typically 3–4 days.

The presented results of the 2013–2022 comprehensive studies of the wind field variability for the atmosphere surface layer and the coastal current are the basis for further research of the formation of the bimodal distribution of alongshore current directions in the inertia-gravity and mesoscale range of wave-eddy fluctuations for periods of 4–5 days.

Conclusion

The peculiarities of the interseasonal variability of the alongshore circulation of coastal waters and wind off the Southern Coast of Crimea were revealed as a result of processing and analysis of materials from long-term *in situ* studies carried out by MHI of RAS at the BSHSTA. The unique opportunity to conduct a long-term (2013–2022) comprehensive *in situ* experiment in the waters of the coastal ecotone near the SCC was ensured by the reliable operation of clusters of domestic oceanological and hydrometeorological meters from the stationary oceanographic platform of the BSHSTA of MHI under open sea conditions.

Comprehensive studies were carried out using verified information technology for instrumental monitoring which ensures high accuracy in long-term instrumental measurements. The results of statistical and spectral analysis were obtained by processing arrays of synchronous databases of variability in the characteristics of coastal current and wind.

1. Intense wind field variability in the atmosphere surface layer is established throughout the entire annual cycle in the range of periods of 12 and 24 h, 4–6 days and 13–21 days with the dominance of alongshore fluctuations of the local wind direction. Therein, regular mesoscale wind fluctuations can be a source of generation of trains of intense short-period internal waves off the coast.

2. Full energy spectra of current and wind fluctuations have close spectral ranges of intensification of fluctuations in the mesoscale and synoptic ranges of variability.

Further identification of statistical cause-and-effect relationships between the characteristics of current and wind fluctuations is a promising task for the physical understanding of their interaction.

3. Synoptic fluctuations of the coastal current at periods of ~12 days have significant interseasonal differences in the upper layer of the sea to depths of 15 m. Further *in situ* and numerical model studies of long-wave motions will reveal the reasons for such differences. Current regional numerical models of coastal water areas can be validated and improved based on representative empirical results.

4. Inertia-gravity fluctuations of the coastal current in the range of periods of 6–36 h have significant interseasonal differences. Therein, further research should also be carried out in the range of short-period gravity internal waves. This allows detailed studying their contribution to the formation of the bimodal distribution of alongshore water circulation directions. Moreover, it is necessary to continue research into the peculiarities of the energy wave-eddy interaction of inertia-gravity and mesoscale disturbances of the alongshore coastal current.

The presented results form the basis for further studies of the multiscale variability of coastal water circulation near the SCC as a significant natural factor influencing the sustainable social and economic development of the Crimean coastal region, and this remains one of the priority tasks of Marine Hydrophysical Institute of RAS.

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About the author:

Alexander S. Kuznetsov, Leading Research Associate, Head of the Shelf Hydrophysics Department, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), Ph.D. (Tech.), **ORCID ID: 0000-0002-5690-5349; Scopus Author ID: 57198997777**, *kuznetsov_as@mhi-ras.ru*

The author has read and approved the final manuscript.