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Original paper

Estimation of the Characteristics of the Wind Field Seasonal Variability Near the Southern Coast of Crimea from Measurements with High Temporal Discreteness

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Abstract
The study is aimed to identify the average for the 12-year monitoring period characteristics of the wind field seasonal variability from measurements with high temporal discreteness. This increased the accuracy of wind characteristic meters during synchronous studies of near-water wind and coastal current variations near the Southern Coast of Crimea. The mean annual characteristics of the coastal wind in the near-water layer of the atmosphere and their seasonal variability were identified by analysing the materials of the database of *in situ* measurements made in 2012–2023 during a complex experiment from the stationary oceanographic platform offshore at Cape Kikineiz. The selected wind characteristics near the coast were compared with the known climate wind characteristics in the region. In the seasonal range of spectral characteristics variability, wind fluctuations at periods of seasonal harmonics I–IV and VI were identified. The energy peak of fluctuations at seasonal harmonic VI was statistically significant both in the wind spectra and coastal current. In the other parts of the spectra, significant differences in the energy distributions of seasonal atmospheric and hydrospheric variations were obvious. Synchronous time series of vector characteristics of coastal wind and current variability were processed using identical information technology. In the intra-annual range of wind variability, we revealed the contribution of the monsoon component as well as seasonal fluctuations of the coastal wind directed along the mountain ridge slope. The range of variability of the studied wind characteristics at sea near Cape Kikineiz was obviously consistent with the characteristics of the regional wind field on land, identified at meteorological stations of the Southern Coast of Crimea. The presented results are necessary for comprehensive studies of the interannual variability of the regional wind field in order to assess statistical relationships with certain variability of the coastal current.

Keywords: *in situ* measurements, wind field, seasonal variations, energy spectrum, Southern Coast of Crimea, Black Sea

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Оценка характеристик сезонной изменчивости поля ветра у Южного берега Крыма по данным измерений с высокой временной дискретностью

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Аннотация
Целью исследования является выделение средних за 12-летний период мониторинга характеристик сезонной изменчивости поля ветра по данным измерений с высокой временной дискретностью, что обеспечило повышение точности измерителей характеристик ветра при синхронных исследованиях колебаний приводного ветра и прибрежного течения у Южного берега Крыма. Среднемноголетние характеристики прибрежного ветра в приводном слое атмосферы и их сезонная изменчивость выделены путем анализа материалов базы данных контактных измерений, выполненных в 2012–2023 гг. при проведении комплексного эксперимента со стационарной океанографической платформы в море у м. Кикинеиз. Выделенные характеристики ветра у побережья сопоставлены с известными климатическими характеристиками ветра в регионе. В сезонном диапазоне изменчивости спектральных характеристик выделены колебания ветра на периодах I–IV и VI сезонных гармоник. Энергетический пик колебаний на VI сезонной гармонике статистически достоверно выражен одновременно в спектрах ветра и прибрежного течения. На других участках спектров очевидны существенные различия в распределении энергии сезонных атмосферных и гидросферных колебаний. Синхронные временны́е ряды векторных характеристик изменчивости прибрежного ветра и течения обработаны в рамках идентичной информационной технологии. Во внутригодовом диапазоне изменчивости ветра выделен вклад муссонной составляющей, а также сезонные колебания прибрежного ветра, направленные вдоль склона горного хребта. Очевидно соответствие диапазона изменчивости исследуемых характеристик ветра в море у м. Кикинеиз и характеристик регионального поля ветра на суше, выделенных на метеостанциях Южного берега Крыма. Представленные результаты необходимы для комплексных исследований межгодовой изменчивости регионального поля ветра в целях оценки статистических связей с определенной изменчивостью прибрежного течения.

Ключевые слова: контактные измерения, поле ветра, сезонные колебания, энергетический спектр, Южный берег Крыма, Черное море

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Introduction

Experimental studies of wind variability in the near-water layer of the atmosphere and its influence on the water circulation of the coastal water area near Cape Kikineiz on the Southern Coast of Crimea (SCC) were initiated in 1929 [1–5] and are ongoing to the present day [6–8]. Concurrently, a sophisticated array of contributions from multi-scale variability to the configuration of the coastal wind field is examined. This involves the conversion of regional baric conditions by the orography of the adjacent mountain massif, the monsoon effect and local winds of thermal origin.

Earlier, based on the analysis of experimental data, the contribution of breeze circulation and slope winds was identified and quantitative estimations of the inter-seasonal differences in the spectral characteristics of the wind daily variability in the coastal zone of the SCC on land and at sea were presented [6, 7]. The variability of wind conditions near the coast causes rearrangement of the structure of the coastal current [1, 4]. In case of obvious dominance of the contribution of intensive hydrodynamic disturbances formed near the coast, the phenomenon of bimodal modulation of the longshore water flow direction appears in the quasi-stationary flow near the SCC [1, 5], the genesis of which was studied in [7, 8]. The present study investigates a set of multi-scale coastal wind fluctuations [7], which form the wind field in the near-water layer of the atmosphere, on the basis of experimental data.

The aim of the present study is to investigate the 12-year average characteristics of seasonal variability of the wind field in the coastal zone near the SCC as well as to identify regularities and structural features in the energy spectra of seasonal fluctuations of the near-water wind and coastal current near Cape Kikineiz in order to estimate statistical relationships.

Materials and methods of study

In situ measurements of wind field characteristics were carried out on the stationary oceanographic platform of the Black Sea Hydrophysical Subsatellite Polygon (BSHSP) of Marine Hydrophysical Institute (MHI) of RAS in Blue Bay near Cape Kikineiz at a distance of ~500 m from the shore [6, 7]. The region-adapted system of MHI BSHSP hydrometeorological monitoring includes a hardware complex of every-second measurements of wind field characteristics in the sea by three sets of meters simultaneously installed compactly on the mast of the oceanographic platform at the height of the place 18 m above sea level. Two sets of anemorumbometers M-63 as part of meteorological complex MHI-6503 [9] and a set of wind speed and direction modulus meters SWS as part of the CSCD complex [10] were used. The measurement results were recorded on autonomous data storage devices and in the operational mode. They were also transmitted via radio communication channel from the platform to the onshore working station. The velocity values were adjusted to a standard observation height of 10 m [11] for the conditions of a logarithmic sublayer of the near-water wind. According to the results of [12], the values of the sea surface roughness parameter near the oceanographic platform were determined within the range of 10^{-4}–10^{-3} m. Wind speed correction was performed at an average value of the sea surface roughness parameter equal to $5–10^{-4}$ m.

Based on the results of instrumental monitoring, annually updated database [1)] of wind characteristics in the near-water layer of the atmosphere near Cape Kikineiz, SCC, was formed. The initial database array generated for the period 2012–2023 contains 105,192 hourly average wind vector values, where each hourly average value is calculated by vector averaging of the hourly wind vector component values. Quality control of wind characteristics measurements is carried out regularly by comparing a set of statistical and spectral indices of certified primary measuring transducers that have passed metrological certification in accordance with the established procedure, which, with a certain redundancy of information, made it possible to exclude the contribution of faulty values and significant systematic errors of measurements from temporal realizations. From the initial array, 4 383 pairs of daily average wind vector components were formed by vector averaging with random error of the velocity modulus measurements not exceeding 0.1 m/s and wind direction 3° [7].

Arrays of vector data of wind characteristics measurements are processed according to the technique developed on the basis of standard methods of mathematical statistics, spectral analysis and digital filtering including centering of vector series. The centering algorithm contains the procedure of vector subtraction of the average vector components from the current values of the vector series components. The spectral analysis of wind circulation variability was performed within the framework of the filter estimation of the full energy spectrum of fluctuations through periodogram smoothing based on the software developed by MHI [6–8]. To minimize the contribution of distortions arising in calculations of the spectral characteristics of the wind field seasonal variability, the contribution of intense fluctuations with periods from one day to three weeks was excluded in the initial vector data array by digital filtering. The structure of wind fluctuations in the specified range of variability was studied in [7].

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1) 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).

The analysis of the structure of multi-scale variability of the wind field characteristics presented in [7] made it possible to optimize the order of application of the processing methodology in the formation of the corresponding arrays for the study of the wind field seasonal variability. The monthly averages of the wind field characteristics were used to estimate the 12-year average characteristics of the wind field, from which the spectral characteristics of the seasonal harmonics of wind fluctuations were also calculated [2)].

The regularities of spatial and temporal variability of wind conditions are investigated on the basis of special processing of the generated data sets for the specified 12-year measurement period. For this purpose, the procedure of selective data filtering is applied to the initial time series. The set of parameters of the data sequential filtering (smoothing) is determined by the choice of the range of the wind field variability under study. After selecting the range of variability under study and its corresponding filtering parameters, the energy spectrum and empirical probability density functions of the wind direction distribution calculated after the data filtering procedure are further calculated. Thus, in [7], the daily range of wind variability was studied and its corresponding filtering parameters were selected. After exclusion of intense wind fluctuations with a period of ~1 day from the initial energy spectrum, the direction of ~355° actually disappears in the initial empirical probability density function of wind direction distribution in the total wind contribution. By excluding the contribution of daily wind fluctuations from the time series, the general direction of local winds with a daily fluctuation period was determined. Other ranges of coastal wind variability including the seasonal range are sequentially investigated in the same way. The sequential filtering procedure used earlier in [13] for investigations of large-scale characteristics of the current field is applied in this processing.

Results and discussion

Within the framework of using a non-standard technique for processing vector-averaged series of wind variability, the following results of investigations of the average wind characteristics for a 12-year period of measurements, spectral characteristics of its seasonal variability as well as spatial and temporal structure of fluctuations of the near-water wind field were obtained.

Average for the 12-year period characteristics of wind. The average characteristics of the north-northeasterly wind (~25°) at a speed of ~1.5 m/s are highlighted for the 2012–2023 measurement period and coincide with the estimates obtained earlier in [7]. The indicated average wind characteristics are compared with the known regime (climatic) wind characteristics in the region. It is stated in [3] that northeasterly winds prevail at Cape Kikineiz during the cold period of the year. The characteristics of large-scale variability of the wind field were

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

previously determined by analyzing the materials of standard meteorological observations, archival data and results of expedition studies. The identified estimates of the indicated mean wind characteristics agree with the values of the direction of the climatic wind field in the Black Sea region presented in work [3)] where the prevalence of the northern quarter winds in the SCC during the entire annual cycle is noted. Characteristics of the typical near-water wind field near the northern Black Sea coast obtained by analyzing synoptic maps [4)] as well as results of previously published generalizations [5)-7)] are consistent with the climatic characteristics of the SCC wind field presented in work [3)]. The results obtained by the non-standard methodology differ from the results obtained by the standard approach traditionally used in meteorology. Thus, if the direction of the average for 12-year period of wind measurements corresponds to the courses of the highest climatic wind frequency, the wind speeds are significantly lower than the usual standard estimations for the region. It is well-known that northerly winds make a particularly significant contribution to the climate in the highlands adjacent to the coast, including Babugan-Yayla and Ai-Petri, during the cold season [5)]. According to meteorological observations in Balaklava, Yalta, Gurzuf, Alushta and Sudak, winds of northern direction prevail clearly on the SCC at this time [5)]. During the cold period of the year, the contribution of local winds to the total coastal wind field decreases, which helps to refine the characteristics of the regional wind field. The results of modern calculations of climatic and seasonal characteristics of wind field variability in the Black Sea region obtained on the basis of numerical reanalyses of atmospheric circulation [14–16] demonstrate that winds of northern directions are pronounced near the SCC during the entire annual cycle. The results of multi-scale modelling studies of circulation in the atmospheric boundary layer, including local winds, mesoscale and synoptic processes [14–18], were used earlier for comparison in [6, 7].

Spectral characteristics of wind seasonal variability. In this study, the characteristics of seasonal wind variability are investigated based on the results of statistical and spectral analyses of field data obtained from instrumental monitoring of wind field variability for 2012–2023.

[3)] Prikhotko, G.F., Tkachenko, A.V. and Babichenko, V.N., 1967. [*Climate of Ukraine*]. Leningrad: Gidrometeoizdat, 413 p. (in Russian).

[4)] Chernyakova, A.P., 1965. Typical Wind Fields of the Black Sea. In: MGMO ChAM, 1965. [*Collection of Works of the Basin Hydrometeorological Observatory of the Black and Azov Seas*]. Leningrad: Gidrometeoizdat. Iss. 3, pp. 78–121 (in Russian).

[5)] Penuygalov, A.V., 1930. [*Climate of Crimea: A Record of Climate Zoning*]. Simferopol: Krymgosizdat, 178 p. Materials on Water Sector of Crimea. Iss. 6. (in Russian).

[6)] Zats, V.I., Lukianenko, O.Ya. and Yatsevich, G.V., 1966. [*Hydrometeorological Regime of the Southern Coast of Crimea*]. Leningrad: Gidrometeoizdat, 120 p. (in Russian).

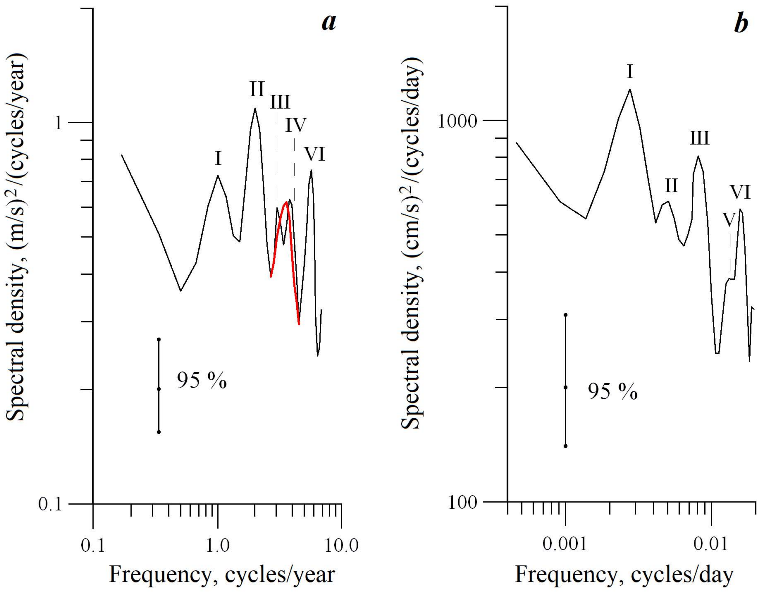
[7)] Logvinova, K.T. and Barabash, M.B., eds., 1982. [*Climate and Dangerous Hydrometeorological Events of Crimea*]. Leningrad: Gidrometeoizdat, 318 p. (in Russian).

As is known, the variability of atmospheric circulation in the Black Sea region is partly connected with the peculiarities of the mechanism of intra-annual development of the monsoon circulation. During the cold period of the year (November–April), local wind speeds near the SCC decrease significantly in the diurnal range of variability compared to the period of intensive breeze circulation (May–October) but at the same time, the intensity of wind fluctuations increases significantly in the range of periods from several days to three weeks [7]. The intensive contribution of multi-scale atmospheric fluctuations distorts constantly the characteristics of the regional wind field during the entire annual cycle. To obtain reliable estimates of the seasonal wind variability, a set of vector-averaged time series was formed, based on which the contribution of intense multi-scale winds was consistently excluded.

The full energy spectrum of seasonal wind fluctuations was calculated from the data of the monthly average series. In the energy density distribution spectrum, reliable energy maxima of wind fluctuations at the annual period and seasonal harmonics are highlighted. It is important to note that, at a certain stage of the spectral processing, the total energy contribution of intense wind fluctuations at periods III and IV of seasonal harmonics is concentrated in the form of a single spectral peak at a period of ~100 days, which is shown in Fig. 1, *a* with a red line.

During the integrated research on the MHI BSHSP stationary oceanographic platform, instrumental measurements of the coastal current characteristics from the surface to the bottom layer are carried out along with monitoring of the wind field characteristics [7, 8]. To compare, Fig. 1, *b* shows average annual full energy spectrum of seasonal fluctuations of surface flow at the hydrological horizon of 5 m. In the current spectrum, reliable energy maxima of fluctuations at the annual (I) period, seasonal harmonics III and VI are highlighted. When comparing synchronously measured characteristics of seasonal wind and current variations, it was found that the spectral peak of variations at seasonal harmonic VI at the period of ~64 days is statistically reliably expressed in the spectrum of wind and coastal current. Other spectral sections revealed structural differences in the energy distribution of atmospheric and hydrospheric fluctuations. The spectral peak of the current variations near seasonal harmonic II is expressed weakly (Fig. 1, *a*) in contrast to the corresponding peak of intense wind fluctuations (Fig. 1, *b*). The energy peak of surface current variations near seasonal harmonic II is weakly pronounced and is highlighted in the area of the fluctuation energy decline with the main annual harmonic. The results of the spectral analysis of the seasonal variability of wind and current make it possible to further estimate statistical relationships and patterns of energy interaction between wind and current in the coastal sea zone.

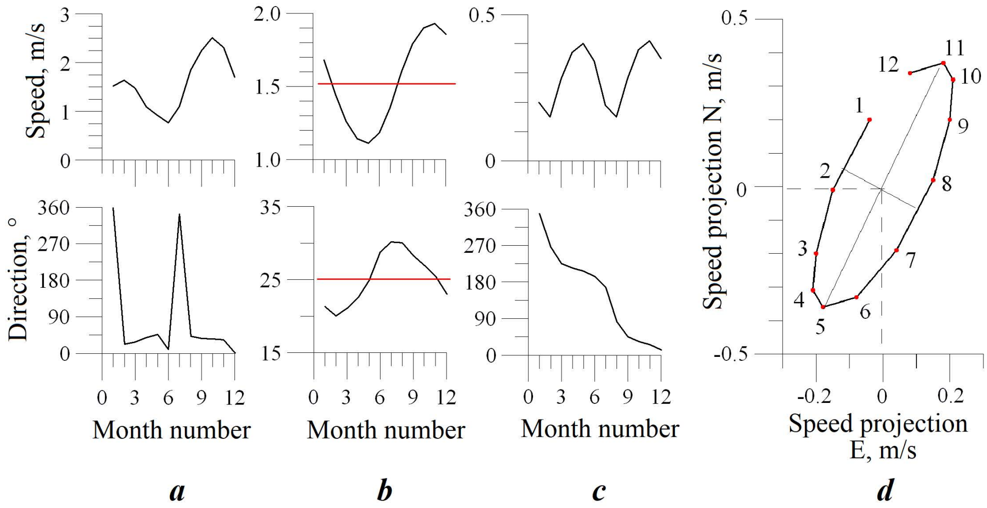
Regularities of intra-annual variability of the 12-year average wind characteristic. The regularities of variability of the indicated wind characteristic were identified by processing monthly averages of wind field components averaged over a 12-year period of measurements. To minimize the contribution of intensive seasonal fluctuations in the range of periods of seasonal harmonics III–VI, the procedure of vector averaging (smoothing) of initial implementation was performed and



F i g . 1 . Average for the 12-year measurement period full energy spectra of seasonal variability of: *a* – wind at the near-water layer of atmosphere with an additional fragment of spectral peak (red line); *b* – current in the near-surface sea layer at corresponding 95% confidence intervals (I–VI are the numbers of seasonal harmonics of fluctuations)

then procedure for centering a smoothed annual average series of monthly wind variability data. The results of processing are presented below. In the process, the monthly mean values of the wind speed and wind direction modulus for each year were sequentially vector-averaged monthly over the entire 12-year measurement cycle. Fig. 2, *a* shows the initial time series of monthly mean values of the wind vector formed in such a way, where maximum values of the monthly average wind speed modulus ~2.5 m/s are identified in October, and minimum values ~0.8 m/s – in June. As it follows from Fig. 2, *a*, the intra-annual variability of mean wind direction is dominated by northerly winds.

Fig. 2, *b* shows seasonal variation of the wind speed and direction modulus when excluding from the initial realization the contribution of intensive wind fluctuations in the range of periods of seasonal harmonics III–VI. The variability of the wind speed modulus time series (Fig. 2, *b*) shows the annual period of fluctuation, where the 12-year average value of the wind speed modulus, equal to ~1.5 m/s, varies within ±0.4 m/s, maximum values of wind speed modulus are



F i g . 2 . Average for the 12-year measurement period time sequences of intra-annual variability of monthly mean wind vector components: *a* – original series; *b* – smoothed series (red lines are vector-averaged for 12 years annual values of corresponding vector components); *c* – centered series (seasonal variability of wind speed for each time series – *top* and directions – *bottom*); *d* – hodograph of seasonal variability of centered wind vector (the numerals denote month number)

identified in November, minimum ones – in May. The value of the direction (~25°) of the north-northeasterly wind varies within ±5°. The maximum values of deviations of the wind direction to the east are identified in July – August and to the west – in January – February.

Fig. 2, *c* demonstrates specified time series of variability of mean monthly variations of the modulus of speed and direction of the centered wind vector. In the time series of variability of centered values of the wind speed modulus (Fig. 2, *c*, *top*), the contribution of seasonal harmonic II of the fluctuation is expressed, with the maximum values of the speed modulus of the centered wind vector identified in May and November and the minimum values identified in February and August. The time series of variability of the centered wind vector direction (Fig. 2, *c, bottom*) shows the annual cycle of the vector reversal at 360°. The regularities of monthly variability of the centered wind vector are clearly demonstrated by the hodograph plotted in the right-hand orthogonal coordinate system oriented to the north (Fig. 2, *d*). The hodograph is shaped like an ellipse, with its major axis aligned with the mean annual wind direction, and a left-handed reversal of the wind speed modulus during the annual cycle. The maximum value of the modulus of the centered wind vector velocity corresponds to point *11* (November) and the minimum to point *5* (May). In both cases, the north-northeasterly wind direction dominates.

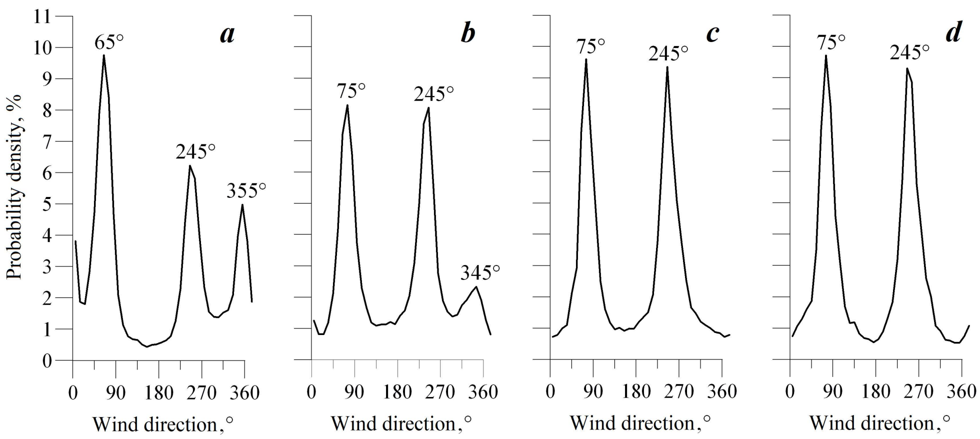
The relevance and physical meaning of *in situ* studies of energy-carrying frequencies of seasonal fluctuations are defined in [19], where it is demonstrated, on the basis of long-term remote satellite measurements of the Black Sea level variability, that the main spectral maxima of sea level fluctuations at periods of seasonal harmonics I and II are caused by corresponding seasonal changes of wind characteristics in the region. The multi-year array of experimental data obtained during the contact monitoring of wind characteristics makes it possible to continue purposefully statistical studies of multi-year spatial and temporal patterns of interannual wind variability in the coastal area of the sea near the SCC.

Regularities of spatial and temporal orientation of seasonal coastal wind fluctuations near the SCC. The total wind field in the region is formed by the interaction of the regional wind with local and local winds. The temporal scales of intense variability of the total wind field in the near-water layer of the atmosphere near Cape Kikineiz are known from the results of spectral analyses of long-term meteorological observations from the stationary oceanographic platform at the Black Sea polygon [6, 7].

The composition of the empirical probability density function of the distribution of coastal wind directions (hereinafter referred to as the empirical function) calculated in ±5° angular segments on the basis of 105,192 hourly averaged data was reliably investigated on the basis of a time series of data on the variability of wind field directions near the coast [1)] (Fig. 3, *a*). In the original empirical function, the contribution of three main wind directions, east-northeasterly, west-southwesterly, and northerly, which have differences in their respective peak probability density values, is evident.

To eliminate distortions introduced by the quasi-stationary average over the 12-year measurement period of the north-northeasterly wind at a speed modulus of 1.5 m/s, the initial series was centered. Fig. 3, *b* shows the results of the centering procedure, where the probability density of the contribution of the winds of east-northeasterly (~75°) and west-southwesterly (~245°) directions has close peaks. Then, following the processing algorithm, the contribution of wind fluctuations at periods 1–3 days to the structure of the empirical function is investigated. Fig. 3, *c* demonstrates the results of this processing stage after digital filtering of the centered time series, during which the contribution of wind fluctuations at periods from 1 to 3 days was excluded. The probability density of the contribution of east-northeasterly and west-southwesterly winds has close peak values.

At the final stage of processing, after removing the contribution of intense wind fluctuations at periods from 4 to 28 days by digital filtering, the contribution of wind fluctuations only at periods of the specified seasonal harmonics is present in the time series. Fig. 3, *d* demonstrates the final empirical function calculated in this process where the value of the integral of the function in the 75 ± 90° range is ~49.6% and in the 245° ± 90° range, it is ~50.4%.



F i g . 3 . Empirical probability density functions of the distribution of wind directions in the near-water atmosphere layer calculated for 2012–2023: *a* – from the initial data; *b* – from centered data; *c* – from centered data when excluding the contribution of fluctuations in the range of periods up to three days; *d* – from centered data on the fluctuations of seasonal harmonics

Based on the results of the presented processing, narrowly directed reciprocating wind fluctuations of east-northeasterly and west-southwesterly directions oriented along the southern slope of the Crimean Mountains ridge adjacent to the coast were identified.

It was determined that in the vicinity of Cape Kikineiz, the spatial and temporal configuration of longshore seasonal wind fluctuations was a permanent feature of the near-water layer of the atmosphere. A comparable configuration of longshore transport of air masses in the surface layer of the atmosphere on land was identified at the meteorological stations of the Southern Coast of Crimea and investigated in [6], in which discrepancies attributable to local features of the relief were documented.

Based on the results of the studies of the seasonal variability of the coastal wind near the SCC, it is possible to estimate the connection between the energy maxima of seasonal wind fluctuations and certain physical processes in the Black Sea region. A significant contribution is made by the seasonal variability of the regional wind field, which is related to seasonal changes in the large-scale atmospheric circulation in the European region and the peculiarities of the mechanism of intra-annual development of the monsoon circulation [4]. In [16], on the basis of numerical modelling, the influence of the Crimean Mountains on the wind regime of the region is noted and it is shown that under certain seasonal conditions, the formation of longshore wind is possible and a mesoscale zone of its speed perturbation is temporarily created. According to the presented empirical results of the research, the quasi-stationary longshore air flow exists permanently, varying in the ranges of mesoscale, synoptic and seasonal wind fluctuations. The exception is the range of daily wind fluctuations.

The results obtained are necessary for investigations of statistical relations of interannual variations of the Black Sea coastal current [20] with the corresponding wind fluctuations in the near-water atmospheric boundary layer.

Conclusion

The information technology for long-term complex studies of variability of wind conditions and water circulation in the sea near the coast with synchronous measurements of vector characteristics with high temporal discreteness was developed and applied. According to the results of analysis of data base materials of instrumental monitoring carried out in 2012–2023 in the sea near Cape Kikineiz, the regularities of seasonal variability of the coastal wind in the near-water layer of the atmosphere near the SCC were identified. The empirical regularities of seasonal fluctuations of the wind field highlighted in the present work permit us to draw the following conclusion. The totality of seasonal, synoptic and mesoscale fluctuations of the coastal wind in the near- water layer of the atmosphere has a pronounced orientation of the air flow along the southern slope of the Crimean Mountains ridge adjacent to the coast throughout the year. Intense local winds are oriented mainly along the normal to the mountain slope adjacent to the coast. The new results of studies of wind variability in the near-water layer of the atmosphere are of practical importance for further studies of the contribution of the coastal wind to the formation of the seasonal and interannual variability of the Black Sea coastal current variations. Such studies are necessary for the development and verification of model predictive systems of coastal water dynamics and ecological and economic monitoring of the coastal water area for sustainable social and economic development of the coastal region.

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Anton V. Garmashov – organisation of and participation in the experiment, processing and analysis of *in situ* data, discussion of the article materials and work results

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