ISSN 1573-160X, *PHYSICAL OCEANOGRAPHY*, Vol. 32, Iss. 3, pp. 297-311 (2025)
Original Russian Text © The Authors, 2025,
published in Morskoy Gidrofizicheskiy Zhurnal, 2025, Vol. 41, Iss. 3, pp. 279–294

Original article

Estimation of the Stationarity Interval of Wind Wave Field

Ya. V. Saprykina ✉, B. V. Divinsky, M. N. Shtremel, O. A. Likutova

Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russian Federation
✉ *saprykina@ocean.ru*

Abstract
Purpose. The wind wave field is non-stationary due to variability of wave formation factors such as wind action and the processes of non-linear wave interactions. However, for many practical applications, it is assumed that the wind wave process, described by some time record of waves, is quasi-stationary. Globally, there is no generally accepted length of a wave record for which the conditions of homogeneity and stationarity of the wave field would be valid. Therefore, the main purpose of the work is to estimate the interval of wave field stationarity based on the data of field contact measurements carried out in the deep-water and coastal zones of the Black Sea in different years and seasons.
Methods and Results. The data from two long-term field experiments in the Black Sea were analyzed. Waves in the open sea were measured using a Directional Waverider buoy, and in the coastal zone – a Spoondrifter Spotter buoy and a resistive string wave gauge, installed on a specialized marine trestle offshore. Spectral analysis methods were applied to the data. The spectral peak width, defined as the peakedness parameter, was used to characterize the homogeneity of wind waves. Wave records containing high values of the peakedness parameter and characterized by a narrow-band spectral distribution, were classified as the cases of quasi-stationary waves homogeneous in their spectral composition close to regular stationary waves. As a result, the characteristic time intervals were obtained for which the wave field could be assumed to be homogeneous and quasi-stationary.
Conclusions. Regardless of the conditions of wave formation, the interval of wave stationarity in the Black Sea can be taken equal to 8–12 minutes. These estimates are the same for the deep-water and coastal parts of the sea, and qualitatively correspond to the theoretical ones.

Keywords: wind waves, wave parameters, wave record length, wave field homogeneity, wave spectrum, stationarity interval

Acknowledgements: The study was carried out with the support of RSF, grant No. 24-27-00082.

For citation: Saprykina, Ya.V., Divinsky, B.V., Shtremel, M.N. and Likutova, O.A., 2025. Estimation of the Stationarity Interval of Wind Wave Field. *Physical Oceanography*, 32(3), pp. 297-311.

Introduction

Understanding the key parameters of wind waves and their spatiotemporal variability patterns is crucial for numerous applications, including forecasting waves, assessing the impact on coastal structures and mitigating operational risks during marine activities. Wind wave field exhibits non-stationary behavior due to variability in wave generation factors, primarily wind forcing and ongoing nonlinear wave interaction processes. Nevertheless, many practical applications employ the assumption that wave processes described by time series records are stationary (or quasi-stationary). This means that their statistical properties remain time-invariant relative to the initial measurement point. This requirement for stationarity is essential for determining wave height probability distributions, which represent the proportion of time during which the recorded wave heights in a time series remain below specified thresholds. The temporal window of wave stationarity is particularly critical for validating satellite wave measurements against *in situ* observations under non-simultaneous sampling conditions. However, empirical evidence demonstrates that wave fields only maintain stationarity within limited temporal windows at any given location. As specified in the international *Coastal Engineering Manual*, wind-generated waves can be considered approximately stationary for periods not exceeding 3 h, beyond this, their properties are expected to change [1].

During the stationarity time interval, the characteristics of the wave record should not change significantly if the duration of the record was slightly shorter or longer, or if sampling was initiated at a slightly different time offset (earlier or later by some fraction of time). If the above-stated assumptions are not satisfied, it signifies that the wave field is non-stationary and cannot therefore be adequately characterized by conventional statistical methods.

From a statistical perspective, an irregular wave field can be fully characterized by a two-dimensional frequency-directional spectrum [1]. Although the sea surface spectrum lacks a precise mathematical form, various empirical models that approximate wave spectra are commonly employed in oceanographic research. These are referred to as parametric spectral models and prove useful for conventional engineering applications. One of the most successful and widely adopted approximations of surface wave frequency spectra is the JONSWAP spectrum, which was proposed in 1973 based on field observations in the North Sea. In its generalized form, it is expressed as [2]:

$$S(f) = \frac{\alpha g^2}{(2\pi)^4} f^{-5} \exp\left(-\frac{5}{4}\left(\frac{f}{f_\mathrm{m}}\right)^{-4}\right) \gamma^{\exp\left(-\frac{1}{2\sigma^2}\left(\frac{f}{f_\mathrm{m}}-1\right)^2\right)},$$

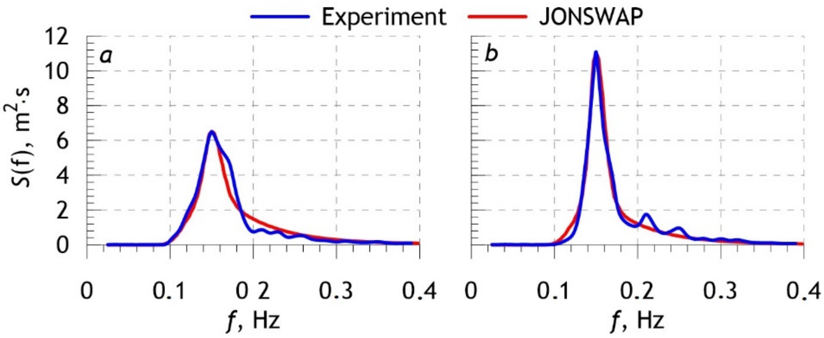
where α is the Phillips constant ($\alpha = 0.0081$); f_m is the spectral peak frequency; γ is the peak enhancement coefficient. The γ parameter represents an extremely important spectral characteristic that controls the shape of the spectrum and determines the distribution of wave energy across the frequency range.

Fig. 1 presents examples of surface wave spectra and their corresponding JONSWAP approximations. The experimental spectra were obtained in the Black Sea using a Datawell Waverider buoy [3]. For the wind waves (shown in Fig. 1, *a* and *b*), the significant wave heights h_s and spectral peak frequencies f_p are identical (~ 2.6 m and 0.15 Hz, respectively), while their shape parameters γ differ substantially (2.6 vs. 5.1).

In other words, Fig. 1 demonstrates that, despite having identical integral wave characteristics (h_s and f_p), the spectral energy distribution differs substantially across frequencies. Higher γ values correspond to a greater concentration of wave energy in the spectral peak region. The absence of anomalously high individual waves in the wave record indicates spectrally homogeneous wave conditions, which are dominated by a single frequency component and thus approximate regular stationary

[1] U.S. Army Corps of Engineers, 2004. *Coastal Engineering Manual*. [online] Available at: https://coastalengineeringmanual.tpub.com [Accessed: 10 May 2025].

waves. This example further reveals that neither wave height nor period can serve as a reliable indicator of wave regularity (homogeneity or stationarity) alone, as neither provides information about spectral composition. The spectral width, which is indirectly characterized by the shape parameter γ, is a more informative metric and is used in wave height distribution assessments [4]. It should be emphasized that, in order to perform a proper spectral analysis of wave records, the data must satisfy the assumptions of wave field stationarity. For example, the *Coastal Engineering Manual* [1] recommends using wave records with durations between 17 and 68 min for spectral analysis.



F i g. 1. Experimental spectra of wind waves and their approximations by the JONSWAP spectrum at h_s = 2.6 m, f_p = 0.15 Hz, γ = 2.6 (*a*) and γ = 5.1 (*b*)

In international engineering practice, the concept of a ‘quasi-stationarity interval’ is used for wave processes. This is conventionally set at 20 min and corresponds to constant external wave generation factors [2]. This terminology has been standardized and widely adopted for instrumental observations of wind wave parameters. Most specialized ocean wave buoys record 20-minute time series of surface elevation data with precision, from which key wave parameters are subsequently derived and statistical analyses are performed. However, these recommendations have traditionally been applied only to deep-water waves. It is questionable whether the ‘quasi-stationarity interval’ concept can be applied to wind waves in coastal zones. Notably, some wave buoy software (e.g., Datawell systems) calculates wave statistics based on 30-minute measurement series. Scientific literature also employs shorter wave record durations – typically 5, 6, 10, or 15 min – for spectral and statistical characterization, as longer series may be non-stationary [5–7]. Theoretical estimates suggest that the quasi-stationarity interval ranges from 10 to 100 characteristic wave period scales τ, where 1 < τ < 10 s [5].

The accuracy of spectral estimates depends on the record length, the temporal resolution (i.e. the sampling frequency) and the method used to smooth the spectral window, in order to achieve an optimal balance between spectral smoothness and the resolution of key components. It should be noted that the specific choice of window function has been shown to have a negligible influence [8].

[2] Lopatukhin, L.I., Bukhanovskii, A.V. and Chernysheva, E.S., 2013. *Reference Data on the Wind and Wave Regime of the Shelf of the Barents and Kara Seas: ND No. 2-029901-01*. Russian Maritime Register of Shipping. St. Petersburg: Publishing Center “Academy”, 335 p. (in Russian).

As previously mentioned, the stationarity assumption is the theoretical basis for deriving wave statistics from field measurements, based on the implicit premise that it is true for all possible sea states. Nevertheless, this assumption has never been systematically validated using extensive field datasets representing diverse wave generation conditions. Consequently, the principal objective of this study is to quantitatively evaluate the duration of wave field stationarity by analyzing direct *in situ* measurements obtained in the Black Sea in different years and seasons, in both the deepwater area and the coastal zone.

In situ data and research methods

The analysis incorporated data from two field experiments conducted at different times in the Black Sea. The first experiment was conducted from 1996 to 2003 and covered all seasonal conditions. Wave parameter measurements were obtained as part of the NATO TU-WAVES international program using a Directional Waverider buoy deployed in the open waters near Gelendzhik (44°30'40N, 37°58'70E). With an installation depth of 85 m, deep-water conditions were ensured for all observed waves, except for anomalous wave events. The buoy operated on a standard 3-hour measurement cycle, transmitting 20-minute records of surface elevation data sampled at a frequency of 1.28 Hz. During periods when the significant wave height exceeded 1.5 m the measurement interval decreased to an hour. The experiment captured a comprehensive range of wave conditions, with measured heights varying from 0.1 to 12 m, and periods ranging from 2.5 to 11.4 s. Full details of the experimental procedures and results can be found in reference [9]. A continuous 70-hour dataset was acquired in April 1998 when the buoy was switched to uninterrupted recording mode. We used this record for detailed analysis.

The second experiment was carried out from September to October 2016 in the coastal area of the Black Sea near the village of Shkorpilovtsi, close to Varna. Wave measurements were taken using three Spoondrifter Spotter buoys, which recorded chronograms of the three components of its displacement at sampling frequency of 2.5 Hz. Simultaneous measurements were performed by an array of four contact wire wave gauges installed on a specialized marine trestle 200 m from the shore.

For the analysis, we used data from a buoy moored at the coordinates 42°95'85N, 27°90'35E at a depth of 12 m, as well as data from a wire wave gauge positioned at the end of the trestle at a depth of 4.5 m, as shown in Fig. 2. During the experiment, measured wave heights ranged from 0.1 to 3 m, with wave periods varying between 2.5 and 10 s.

The key wave parameters were determined by analyzing the frequency spectra and their corresponding spectral moments. These spectral moments are expressed as follows:

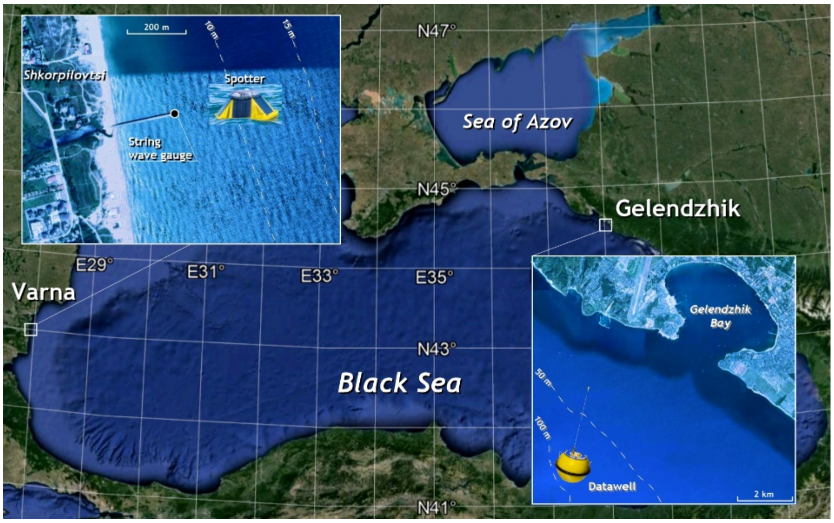
$$M_n = \int f^n S(f) df.$$

The significant wave height

$$h_s = 4\sqrt{M_0} \quad (1)$$

and the mean wave period were calculated using them

$$t = M_0/M_1. \quad (2)$$



F i g. 2. Location of wave recording devices

The spectral peak width, as defined in the manual [3], was considered a characteristic of the irregularity of wind waves in the form

$$\varepsilon = \sqrt{\frac{M_0 M_4 - M_2^2}{M_0 M_4}}. \tag{3}$$

The parameter ε ranges from 0, which corresponds to a narrow spectrum of regular waves, to 1, which is characteristic of a broad spectrum representing an irregular wave field. Since the spectral width in formula (3) is highly sensitive to the quality of the input data, reference [10] proposed an alternative metric: the spectral peakedness parameter, which is defined as the ratio

$$Q = \frac{2}{M_0^2} \int_0^\infty f S(f)^2 df. \tag{4}$$

The peakedness parameter Q assumes values greater than one. Increasing Q values correspond to progressively narrower spectra.

As already noted in the introduction, a narrow spectrum indicates a wave field that is fairly uniform in composition and close to the property of stationarity found in regular waves.

Two methods were used for spectrum construction: parametric spectral analysis (for deep-water waves) and the Welch method with a Hamming window (for coastal zone waves) [11]. The Welch method averages spectral estimates over overlapping segments of the wave record. Thus, the frequency resolution of the obtained spectral estimates is determined by the length of these segments. In this study, this remained constant at 0.02 Hz, independent of the duration of the wave record. The same

[3] WMO, 2018. *Guide to Wave Analysis and Forecasting*. Geneva: World Meteorological Organization, 208 p. (WMO-No. 702). [online] Available at: https://library.wmo.int/records/item/31871-guide-to-wave-analysis-and-forecasting [Accessed: 10 May 2025].

frequency resolution was adopted for the parametric method. Assessments were made of the influence of the spectrum construction method on the obtained spectral characteristics.

The analysis demonstrated that spectral estimates are practically independent of the spectrum construction method, particularly the shape of the smoothing window, but depend significantly on the frequency resolution. This is fully consistent with the theoretical concepts outlined in reference [8]. For instance, a frequency resolution of 0.1 Hz yields identical spectral estimates regardless of record length, as the resulting spectrum is excessively smoothed and broad. As noted in references [8, 11], selecting spectral estimation parameters involves compromising between resolving power and spectrum smoothing when considering the characteristics of the target process under study. In our study, we specifically chose a resolution of 0.02 Hz to clearly identify the second nonlinear harmonic in the spectrum, which influences many dynamic processes in the coastal zone of the sea [12].

Additionally, assessments were made of the variability of higher-order wave moments for coastal zone conditions. These moments serve as specific indicators of nonlinear wave interactions and are frequently used in engineering and predictive models. Applications include determining the direction and magnitude of bedload sediment transport in coastal areas [13–15] and estimating the probability of abnormally high waves [16].

The study examined the third-order wave moments, namely vertical axis asymmetry *As* and horizontal axis skewness *Sk*, as well as the fourth-order moment *K*, kurtosis. These parameters were calculated using the formulas presented in references [16; 17, p. 1726]:

$$As = {\langle H(\xi)^3 \rangle} \big/ {\langle \xi^2 \rangle^{3/2}}, \tag{5}$$

$$Sk = {\langle \xi^3 \rangle} \big/ {\langle \xi^2 \rangle^{3/2}}, \tag{6}$$

$$K = {\langle \xi^4 \rangle} \big/ {\langle \xi^2 \rangle^{2}}, \tag{7}$$

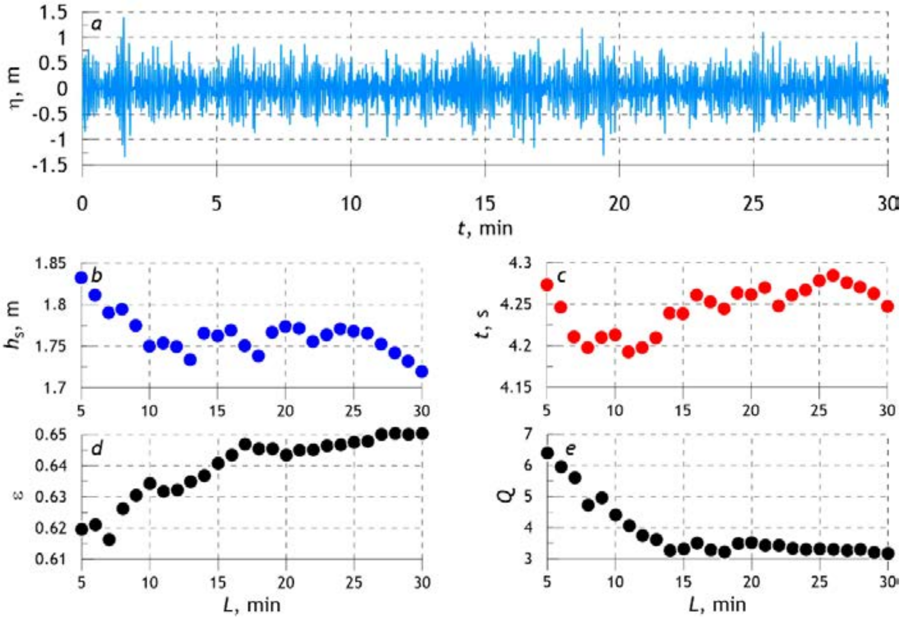
where ξ is the chronogram of the free surface elevation (wave); H is the Hilbert transform; angle brackets indicate time averaging.

Results and discussion

Temporal wave field homogeneity in the deepwater area

We analyzed a continuous 70-hour record from the Datawell buoy and generated 140 time series of surface elevation, each lasting 30 min. For each 30-minute time series, we first calculate the spectral characteristics for the first 5 minutes of the record. We then incrementally increase the length L of the wave chronogram by 1 min until it reaches 30 min. Fig. 3 shows an example of this processing for one 30-minute record.

As evident from Fig. 3, increasing the chronogram length from 5 to 30 min has a negligible influence on the calculated significant wave heights (1) and mean periods (2). The spectral bandwidth (3) (Fig. 3, *d*) initially increases, but then stabilizes after $L = 17$ min. At the same time, the ε parameter varies insignificantly in absolute value. In contrast, the peakedness parameter Q demonstrates a slight increase at record lengths of 8–9 minutes, followed by a decrease until L reaches 14 min. When the chronogram length L increases from 14 to 30 min, the value of the peakedness parameter remains almost unchanged.



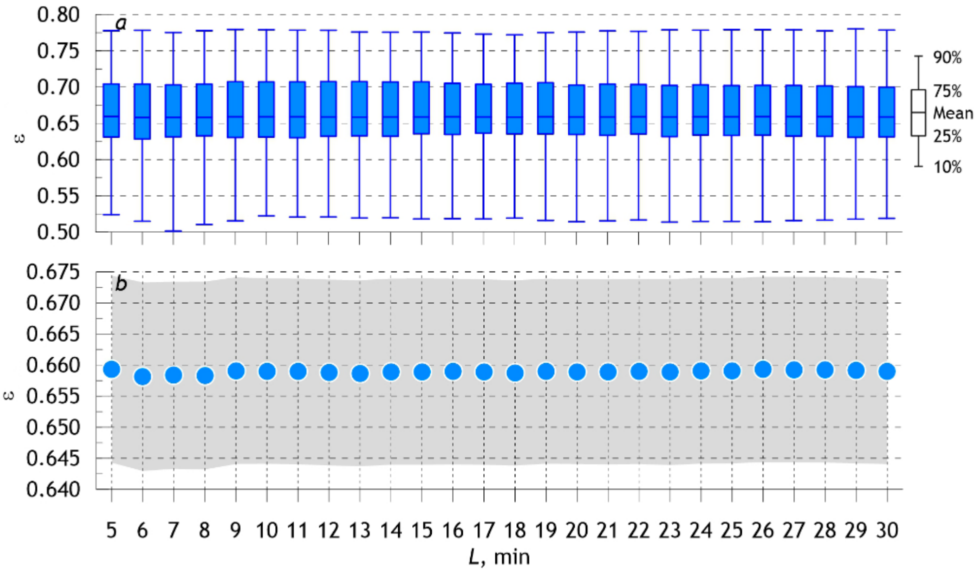
F i g. 3. Free surface elevation (*a*), significant wave heights (*b*), average periods (*c*), spectrum width (*d*), and peakedness parameter (*e*) for successive chronograms of L length

These patterns, however, reflect just a single observational series. To derive statistically robust conclusions, we aggregated the results from all the available records (140 chronograms of 30-minute waves).

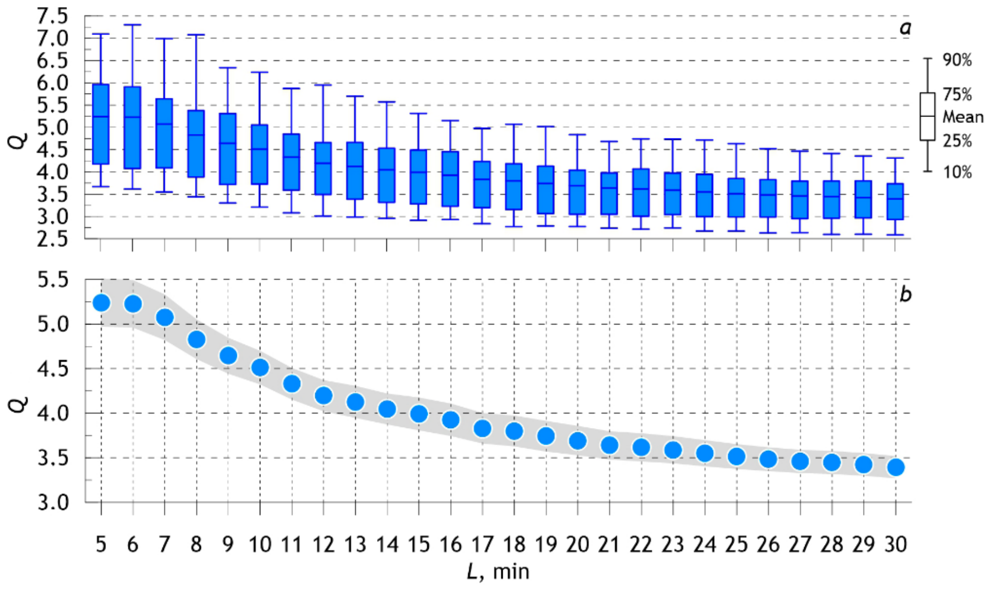
Fig. 4, a presents graphical estimates of the mean value of spectral bandwidth, along with the 10^{th}, 25^{th}, 75^{th}, and 90^{th} quantiles of the distribution. Fig. 4, *b* displays the mean values alongside the 95% confidence intervals (gray shaded area). As can be seen clearly from Fig. 4, the statistical characteristics of spectral bandwidth remain independent of realization length. Therefore, the spectrum width determined by formula (3) is uninformative for our purposes and not suitable for analyzing wave irregularity.

Fig. 5 presents similar plots for the peakedness parameter Q, which is calculated using formula (4). As can be seen in Fig. 5, there is a relatively sharp decrease in the mean value of the peakedness parameter in the range where the chronogram length L increases from 6 to 12 min. For record lengths $L > 12$ min, the Q parameter also decreases, but much more slowly. For record lengths $L > 22$ min, Q remains almost unchanged, apparently due to the increasing spectral bandwidth preventing detailed resolution of its shape. We also observe the narrow range of 95% confidence intervals (grey area in Fig. 5, *b*) for the mean value.

To expand the statistical basis of the study, we used archival data comprising 20-minute surface elevation records from 1998. These records cover the entire range of observed wind-wave conditions, from calm to stormy. There are a total of 1,100 of such records.

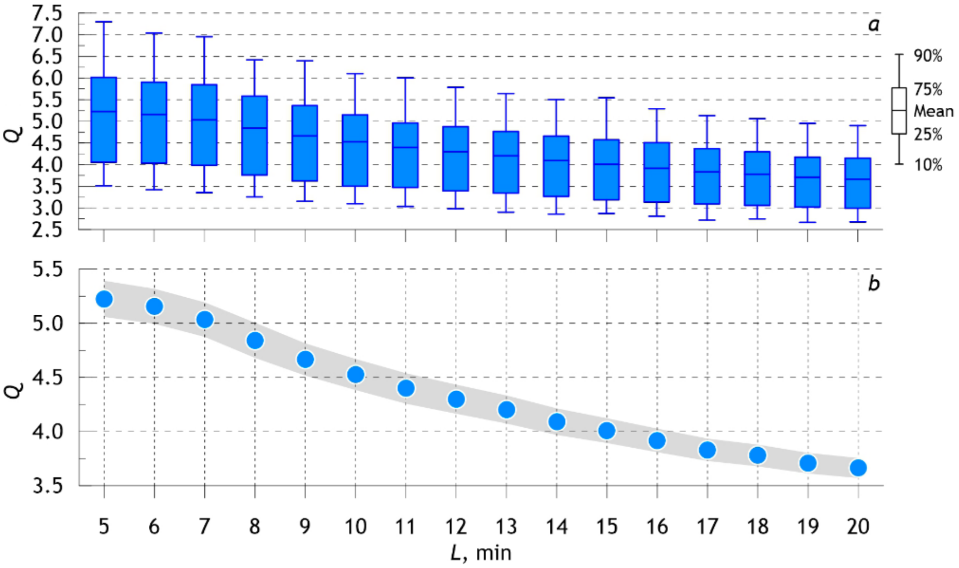


F i g. 4. Statistical characteristics of the distributions of spectrum width values (*a*) as well as the average spectrum width values (*b*) for successive series of free surface elevations of *L* length



F i g. 5. Statistical characteristics of the distributions of peakedness parameter values (*a*) as well as the average spectrum width values (*b*) for successive series of *L* length equal to 5, 6, …, 30 min

Fig. 6 shows the results of analyzing all these records. The analysis reveals that, as the chronogram length increases from 7 to 20 min, the peakedness parameter decreases. This process is two-stage: a rapid increase in the parameter is observed as the chronogram length increases from 7 to 12 min, while a slower decrease takes place as it increases to 20 min. This is consistent with the patterns identified for continuous recording (Fig. 6). The *Q* values remain relatively high for record lengths up to approximately 8 min, indicating a narrow spectral bandwidth characteristic of regular wave conditions. Based on this, we can conclude that the wave field has a uniform spectral composition for a time interval of up to 8 min. When the record is extended to 12 min, the Q parameter values decrease but still remain high. Therefore, we can assume that the wave field will be close to uniform for no more than 12 min.



F i g. 6. Statistical characteristics of the distributions of peakedness parameter values (*a*) as well as the average spectrum width values (*b*) for successive series of free surface elevations of *L* length

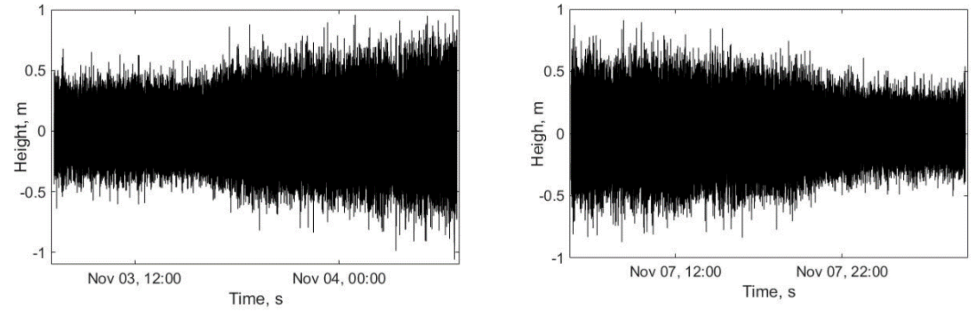
Thus, the peakedness parameter proves to be an effective tool for analyzing the spectral structure of waves in terms of their irregularity. Surface elevation records with durations of up to 12 min can be classified as spectrally quasi-homogeneous wave cases and treated as nearly stationary wave conditions. These findings are notable because they remain independent of wave generation conditions and the development stage of wind waves.

Temporal homogeneity of the wave field in the coastal zone of the sea

The results obtained for waves in deepwater area in the previous section are fully confirmed for waves in the coastal zone of the sea. We will consider them using two daily chronograms as an example. To assess the influence of wave formation conditions more precisely, we selected two 24-hour wave records corresponding to an increase (3–4 November 2018) and a decrease (7–8 November 2018) in wave height (Fig. 7).

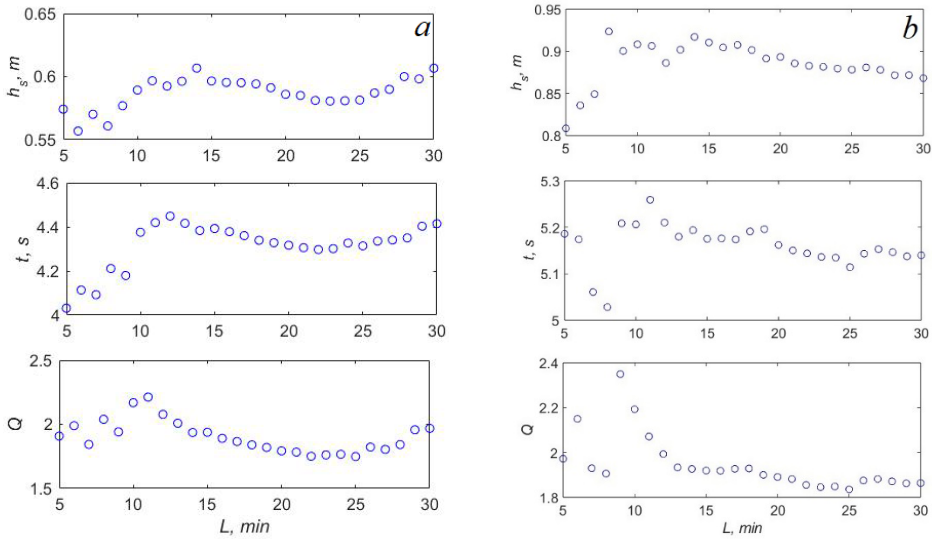
Since the position of the buoy relative to the anchor changes depending on the direction of the wind and currents, synchronous records of surface elevation obtained from a stationary resistive wave gauge on 7–8 November 2018 were used to assess the influence of buoy mobility on the obtained data. The wave gauge was installed at the end of the trestle at a depth of 4.5 m.

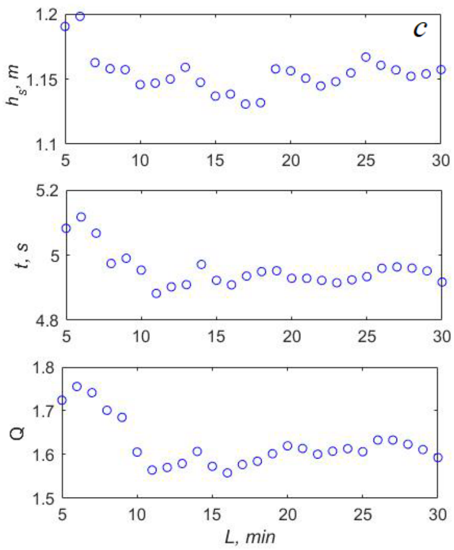
Fig. 8 shows how significant wave height, mean period and parameter Q vary with the length of the record used for estimation when comparing data from the buoy and the stationary wave gauge.



a *b*

F i g. 7. Wave chronograms recorded by the Spoondrifter buoy in the Black Sea coastal zone on 3–4 November (*a*) and 7–8 November (*b*) 2018 and used for analysis





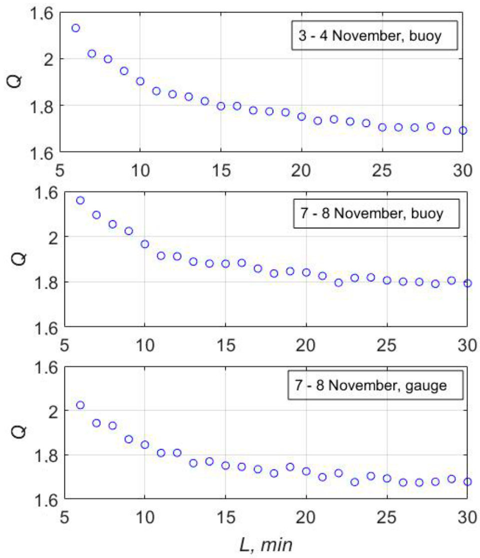
F i g. 8. Dependences of significant wave height, average period and spectrum peakedness parameter on the chronogram length L based on the buoy data from 3 November (*a*) and 7 November (*b*) 2018 and the stationary wave recorder data from 7 November 2018 (*c*)

The results demonstrate that increasing the record length has a minimal effect on the values obtained for wave height and mean period. When the record length exceeds 12 min, the differences become negligible. As with deepwater waves, the spectrum peakedness parameter demonstrates a sharp decrease as the record length increases from approximately 7–9 min to 12 min, followed by insignificant subsequent changes. The variations observed for record lengths shorter than 8 min (Fig. 8, *a*, *b*) may be attributed to the specific characteristics of these records. The duration of the records may be insufficient to mitigate the effects of buoy mobility, as such variations are not present in measurements obtained from the stationary wire wave gauge. Furthermore, these deviations are not observed when averaging across all realizations.

The average values of peakedness parameter for the selected 24-hour records are given in Fig. 9.

As with deep-water waves (see Fig. 6), the decrease in the peakedness parameter with increasing chronogram length occurs in two distinct temporal phases: a rapid reduction when extending the record from 6 to 12 min, followed by a more gradual decline as the record length increases to 20 min. The absolute *Q* parameter values remain relatively high (indicating a narrow spectrum) for records shorter than 8 min, suggesting that the wave field maintains spectral homogeneity for approximately 8 min and near-homogeneity for up to 12 min. Records extending beyond 20 min do not allow us to identify the features of the spectrum shape, providing almost identical *Q* parameter values.

Thus, regardless of the conditions of wave generation and propagation (in deep water or in the coastal zone), the approximate duration of homogeneity, and consequently of stationarity, for surface elevation records is about 8 min. Records of up to 12 min can be considered to be approximately homogeneous (quasi-stationary). These estimates are in full agreement with theoretical predictions [5]. The examined wave conditions had characteristic time periods (spectral peak periods) ranging from 5 to 7 s, and theoretical estimates suggest maximum quasi-stationarity durations of 100 characteristic periods (from 500 to 700 s, or approximately 8 to 12 min).



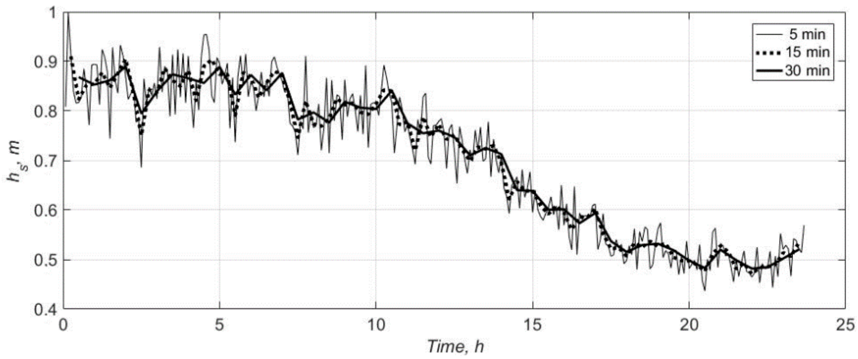
F i g. 9. Dependence of the average values of spectrum *Q* peakedness parameter upon the *L* length of successive series of free surface elevations in the Black Sea coastal zone

Analysis of higher spectral moments

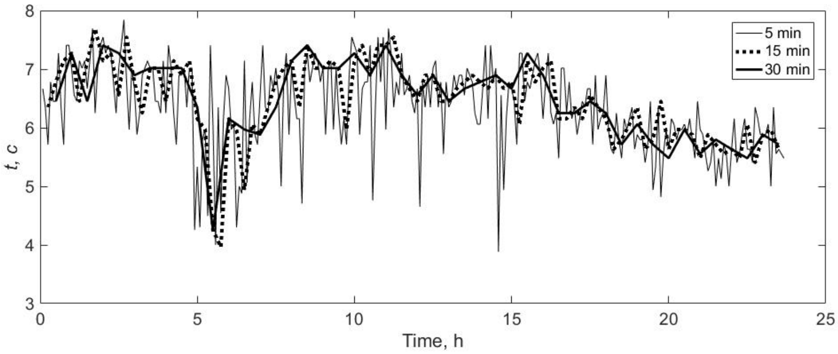
Using a daily record of decaying waves measured by a buoy on 7–8 November 2018 (Figs. 10, 11), we consider how the length of the record affects the obtained estimates of wave height, average period, and the value of higher wave moments that determine the shape of the waves.

In general, the trend in variation of the selected wave parameters over the 24-hour period is the same, regardless of the duration of the chronogram used. However, the shorter the chronogram used for assessment, the greater the absolute changes for all parameters. As the length of the record used for calculation increases, the spread of absolute values decreases. Therefore, the spread of values for 5- and 30-minute records is up to 10% for height variation and up to 50% for changes in the average wave period, regardless of the wave attenuation stage. Values of selected wave parameters calculated from 10- to 20-minute records differ by only 2–3%. Values obtained from 30-minute records are smoother.

Wave shape parameters, obtained from 30-minute chronograms, such as wave asymmetry values relative to the vertical and horizontal axes, practically never take negative values. This can lead to incorrect estimates of sediment transport direction.

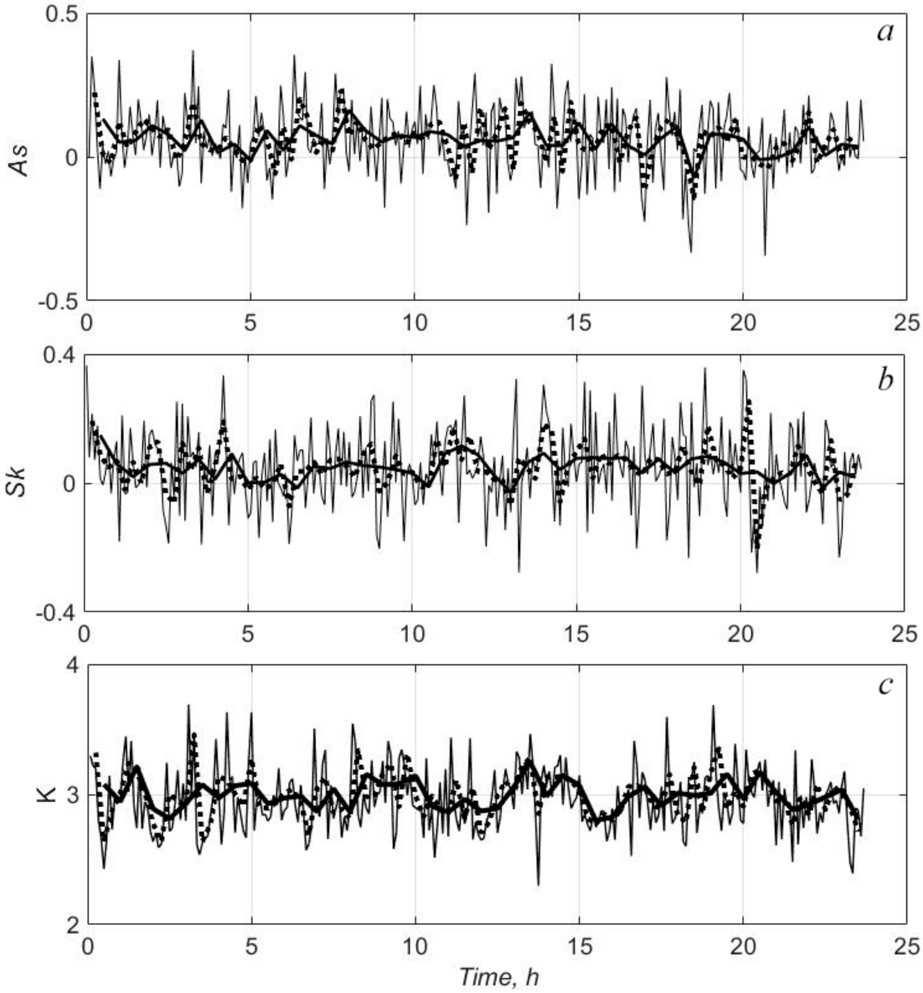


a



b

F i g. 10. Changes in significant wave height (*a*) and average wave period (*b*) based on the chronograms of different lengths for a 24-hour record made on 7–8 November 2018



F i g. 11. Change in wave asymmetry described by formulas (5)–(7) and calculated using the chronograms of different lengths for a 24-hour record made on 7–8 November 2018: a – *As*; *b* – *Sk*; *c* – *K*

Conclusions

The research results indicate that the period of wave field stationarity in the Black Sea can be reliably established as 8–12 min, independent of wave generation conditions. These estimates demonstrate complete consistency between the deepwater and coastal zones of the sea. Their qualitative correspondence with theoretical estimates suggests that this result is universal across the entire World Ocean.

Analysis of higher-order wave moments and spectral shape characteristics using the peakedness parameter *Q* reveals greater variability when derived from wave records shorter than the determined period of stationarity.

REFERENCES

1. Longuet-Higgins, M.S., Cartwright, D.E. and Smith, N.D., 1963. Observation of the Directional Spectrum of Sea Waves Using the Motions of a Floating Buoy. In: National Academy of Sciences, 1963. *Ocean Wave Spectra: Proceedings of a Conference*. Prentice-Hall, Englewood Cliffs, N.J., pp. 111-132.
2. Hasselmann, K., Barnett, T., Bouws, E., Carlson, H., Cartwright, D., Enke, K., Ewing, J.A., Gienapp, H., Hasselmann, D.E. [et al.], 1973. Measurements of Wind-Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP). *Erganzungsheft zur Deutschen Hydrographischen Zeitschrift.* Reihe A, Nr. 12, 95 p.
3. Divinsky, B.V., 2003. Results of Measuring of Surface Waves Parameters with Help of Buoy in Gelendzhik Area. In: R. D. Kos'yan, I. S. Podymov and N. V. Pykhov, eds., 2003. *Dynamical Processes in the Sea Nearshore Zone*. Moscow: Scientific World. pp. 70-91 (in Russian).
4. Tayfun, M.A., 1983. Effects of Spectrum Band Width on the Distribution of Wave Heights and Periods. *Ocean Engineering*, 10(2), pp. 107-118. https://doi.org/10.1016/0029-8018(83)90017-3
5. Efimov, V.V. and Polnikov, V.G., 1991. *Numerical Modeling of Wind Waves*. Kiev: Naukova Dumka, 238 p. (in Russian).
6. Trubkin, I.P., 2003. [Method and some Results of Directional Spectra Estimations of Random Waves Field in the Coastal Zone]. *Ecological Systems and Devices*, (9), pp. 47-53 (in Russian).
7. Vapnyar, M.U. and Tatlyeva, Z.I., 1989. [On the Nature of the Long-Term Distribution of Wave Heights in the Caspian Sea]. *Trudy GOIN*, 188, pp. 132-137 (in Russian).
8. Jenkins, G.M. and Watts, D.G., 1969. *Spectral Analysis and Its Applications*. Holden-Day, San Francisco, 541 p.
9. Divinskii, B.V., Kos'yan, R.D., Podymov, I.C. and Pushkarev, O.V., 2003. Extreme Waves in the Northeastern Black Sea in February 2003. *Oceanology*, 43(6), pp. 891-893.
10. Goda, Y., 1970. Numerical Experiments on Wave Statistics with Spectral Simulation. *Report of the Port and Harbour Research Institute*, 9(3), pp. 3-57.
11. Marple, S.L.Jr.,1987. *Digital Spectral Analysis with Applications*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 492 p.
12. Saprykina, Ya.V., Kuznetsov, S.Yu., Andreeva, N.K. and Shtremel, M.N., 2013. Scenarios of Nonlinear Wave Transformation in the Coastal Zone. *Oceanology*, 53(4), pp. 422-431. https://doi.org/10.1134/S0001437013040103
13. Bailard, J.A., 1981. An Energetics Total Load Sediment Transport Model for a Plane Sloping Beach. *Journal of Geophysical Research: Oceans*, 86(C11), pp. 10938-10954. https://doi.org/10.1029/JC086iC11p10938
14. Ruessink, B.G., Van Den Berg, T.J.J. and Van Rijn, L.C., 2009. Modeling Sediment Transport beneath Skewed Asymmetric Waves above a Plane Bed. *Journal of Geophysical Research: Oceans*, 114(C11), C11021. https://doi.org/10.1029/2009JC005416
15. Saprykina Y., 2020. The Influence of Wave Nonlinearity on Cross-Shore Sediment Transport in Coastal Zone: Experimental Investigations. *Applied Sciences*, 10(12), 4087. https://doi.org/10.3390/app10124087
16. Wang, L., Zhou, B., Jin, P., Li, J., Liu, S. and Ducrozet, G., 2022. Relation between Occurrence Probability of Freak Waves and Kurtosis/Skewness in Unidirectional Wave Trains under Single-Peak Spectra. *Ocean Engineering*, 248, 110813. https://doi.org/10.1016/j.oceaneng.2022.110813
17. Elgar, S., 1987. Relationships Involving Third Moments and Bispectra of a Harmonic Process. *IEEE Transactions on Acoustics, Speech, and Signal Processing*, 35(12), pp. 1725-1726. https://doi.org/10.1109/TASSP.1987.1165090

About the authors:

Yana V. Saprykina, Leading Research Associate, Shirshov Institute of Oceanology, Russian Academy of Sciences (36 Nakhimovsky Avenue, Moscow 117997, Russian Federation), CSc. (Phys.-Math.), **Scopus Author ID: 57217957923**, **ORCID ID: 0000-0003-0357-0773**, saprykina@ocean.ru

Boris V. Divinsky, Leading Research Associate, Laboratory of Geology and Lithodynamics, Shirshov Institute of Oceanology, Russian Academy of Sciences (36 Nakhimovsky Avenue, Moscow 117997, Russian Federation), CSc. (Geogr.), **ORCID ID: 0000-0002-2452-1922**, **Scopus Author ID: 6508359174**, **ResearcherID: C-7262-2014**, divin@ocean.ru

Margarita N. Stremel, Senior Research Associate, (36 Nakhimovsky Avenue, Moscow 117997, Russian Federation), CSc. (Geogr.), **Scopus Author ID: 55844240900**, **ORCID ID: 0000-0003-0045-0282**, shtremel@ocean.ru

Olga A. Likutova, Junior Research Associate, Shirshov Institute of Oceanology, Russian Academy of Sciences (36 Nakhimovsky Avenue, Moscow 117997, Russian Federation), CSc. (Geogr.), **Scopus Author ID: 57104743100**, **ORCID ID: 0000-0002-7013-339X**, olga.ku-ocean@yandex.ru

Contribution of the co-authors:

Yana V. Saprykina – developing the main idea and concept of the paper, obtaining and analyzing data for waves in the coastal zone, figure preparation, writing the text and working on the reviewer's comments, writing the final version of the paper

Boris V. Divinsky – proposing and discussing analysis methods, analyzing data for deepwater waves, figure preparation, writing a part of the text

Margarita N. Stremel – obtaining and pre-processing experimental data in the coastal zone, figure preparation

Olga A. Likutova – writing part of the introduction, preliminary processing of experimental data in the coastal zone

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