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Probability of the Appearance of Abnormal Waves in the Coastal Zone of the Black Sea at the Southern Coast of Crimea

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Abstract
The paper analyzes the probability of appearance of abnormal waves in the coastal zone of the Black Sea. The analysis is based on the data of wave measurements carried out on a stationary oceanographic platform of the Marine Hydrophysical Institute of RAS. Two indices were used to identify abnormal waves. The first index AI is the ratio of the maximum and significant wave heights, the second index CI is the ratio of the maximum crest height and significant wave height. The values of the AI index are mainly in the range from 1.25 to 2.75, the values of the CI index are in the range from 0.7 to 1.5. It is shown that both indices are statistically independent of the steepness and the skewness, a high correlation is observed only with the excess kurtosis λ_4. The correlation coefficients between AI and λ_4 and between CI and λ_4 are 0.57 and 0.49, respectively. The probability of appearance of abnormal waves calculated on the basis of the AI index is higher than that calculated on the basis of the CI index. This is explained by the fact that there are three forms of abnormal waves, which are identified as follows: positive form, whose crest is more than 50 % higher than its trough with respect to the mean sea level, negative form, whose troughs are more than 50 % greater than their crests and a sign-variable form (intermediate). The CI index does not allow distinguishing abnormal waves of a negative form and not always distinguishes abnormal waves of a sign-variable form. The correlation coefficient between indices AI and CI is 0.64.

Keywords: abnormal wave, abnormality index, steepness, skewness, excess kurtosis, Black Sea

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Вероятность появления аномальных волн в прибрежной зоне Черного моря у Южного берега Крыма

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Аннотация
Проведен анализ вероятности появления аномальных волн в прибрежной зоне Черного моря. Анализ основан на данных волновых измерений, проведенных на стационарной океанографической платформе Морского гидрофизического института РАН. Для выделения аномальных волн использовались два индекса. Первый индекс AI является соотношением максимальной и значимой высот волн, второй индекс CI является отношением максимальной высоты гребня и значимой высоты волн. Значения индекса AI в основном лежат в пределах от 1.25 до 2.75, значения индекса CI – в пределах от 0.7 до 1.5. Показано, что оба индекса статистически не зависят от крутизны волн и коэффициента асимметрии, высокая корреляция наблюдается только с коэффициентом эксцесса λ_4. Коэффициенты корреляции между AI и λ_4 и между CI и λ_4 соответственно равны 0.57 и 0.49. Вероятность появления аномальных волн, рассчитанная на основе индекса AI, выше, чем рассчитанная на основе индекса CI. Это объясняется тем, что существуют три формы аномальных волн, которые идентифицируются следующим образом: положительная, при которой высота гребня в полтора раза больше глубины впадины, отрицательная, при которой глубины впадины в полтора раза больше высоты гребня, и знакопеременная (промежуточная). Индекс CI не позволяет выделять аномальные волны отрицательной формы и не во всех ситуациях выделяет аномальные волны знакопеременной формы. Коэффициент корреляции между индексами AI и CI равен 0.64.

Ключевые слова: аномальные волны, индекс аномальности, крутизна, коэффициент асимметрии, коэффициент эксцесса, Черное море

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Introduction

Despite their long history, the studies of the conditions resulting in the appearance of abnormally high waves have been continuing to attract increased attention. Several physical mechanisms can answer for the appearance of abnormally high waves [1, 2]. In deep water, such mechanisms are as follows: modulation instability of wave packets [3, 4]; nonlinear dispersive focusing [5, 6]; interaction with currents [7]; geometric focusing and nonlinear interaction of nonparallel wave systems [8, 9].

To identify abnormal waves such a criterion as AI (abnormality index) is used [10–12]

$$\mathrm{AI} = H_{\max} / H_S ,$$

where $H_{\max}$ – maximum wave height during the measurement period; H_S – significant wave height equal to the average height of one third of the highest waves. The waves with their height, which is more than two times greater than the significant height of background waves, i.e. the waves, for which the following condition is satisfied:

$$\mathrm{AI} > 2 , \quad (1)$$

are considered to be abnormal ones. In recent years, intensive attempts have been made to find a relationship between the appearance of abnormal waves and the characteristics of the sea surface state [12].

The probability that AI > 2 (it will be denoted as P_A) varies over a broad area depending on the region, which is possible due to the variety of physical mechanisms resulting in the appearance of abnormal waves. Measurements taken off the western coast of India show P_A = 0.46 % [11]. Measurements taken under stormy conditions with a downward radar on two platforms in the North Sea, with a wave recorder on a platform in the Gulf of Mexico, and with a wave buoy off the coast of Portugal, show that the average P_A makes 3.6 % [13].

The purpose of this work is to analyze the dependence of the AI index on the integral parameters characterizing the state of the sea surface in the coastal zone of the Black Sea.

Measurements of wave parameters and measurement conditions

The surface wave measurements were carried out on a stationary oceanographic platform of the Marine Hydrophysical Institute of RAS located in the coastal zone of the Black Sea, near the South Coast of Crimea. The minimum distance from the platform to the coastline makes about 600 m. The depth of the sea at the point where the platform is located makes about 30 m. To measure the parameters of the waves, a resistive wave recorder was used, with its sensor represented by a nichrome string wound with fixed spacing on the carrying wireline. To minimize the effect of sea surface disturbances created by the platform supports, wave measurements were carried out at a point at least 6 m away from the nearest support. The description of the measuring equipment and conditions for carrying out measurements on a stationary oceanographic platform is given in [14–17].

Wave and wind speed measurements were carried out regularly from 01.05.2018 to 31.01.2019 with several short breaks. Continuous measurements were divided into periods lasting 20 min. For each period, the statistical characteristics of the waves were calculated, as well as the average wind speed and direction. The total amount of data is more than 17,000 measurement periods.

During the whole period, the wind speed varied from free from rough activity of water to 26 m/s, with the maximum significant wave height H_S – 2.3 m, and the maximum wave height $H_{\max}$ – up to 5.0 m. The probability density empirical

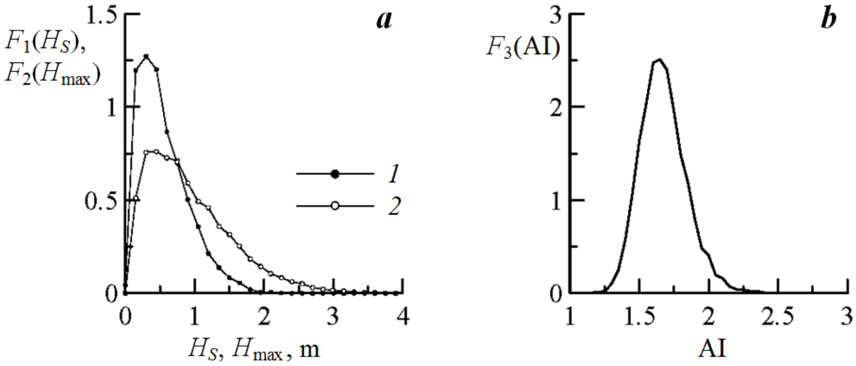


Fig. 1. Distributions of surface wave characteristics during the measurement period: *a* – significant wave height $F_1(H_S)$ (curve *1*) and maximum height $F_2(H_{max})$ (curve *2*), *b* – abnormality index F_3(AI)

functions of these wave parameters denoted as $F_1(H_S)$ and $F_2(H_{max})$ are shown in Fig. 1. Fig. 1 also shows the probability density empirical function of the abnormality index $F_3(AI)$.

The AI values obtained for the coastal zone of the Black Sea lie in the following range: 1.1 < AI < 2.8. The probability of occurrence of abnormal waves with AI > 2 made 3.3 %.

Correlation of AI abnormality index with steepness and skewness

Nonlinear physical mechanisms result in the appearance of abnormal waves [12]. To compare the relative level of nonlinearity, the steepness of the waves is used [18, 19]. The steepness of gravity waves in deep water satisfying the dispersion relation $\omega^2 = gk$ is defined as follows

$$\varepsilon = \sqrt{\overline{\xi^2}}k_0 = \sqrt{\overline{\xi^2}}\,\omega_0{}^2/g\,,$$

where $\overline{\xi^2}$ – sea surface elevation dispersion; k – wave number; ω – frequency; g – gravitational acceleration; index "0" means that this parameter corresponds to a peak in the wave spectrum.

The correlation between the abnormality index and the steepness of the waves is shown in Fig. 2. It can be seen that AI is almost independent of the steepness of the waves. The correlation coefficient between AI and ε makes 0.06.

A consequence of the nonlinearity of sea surface waves is the deviation of the distribution of sea surface elevations from the Gauss distribution. The main parameters that describe the effect of nonlinearity on the geometric characteristics of waves are skewness and excess kurtosis [9, 19], which can be used as a measure

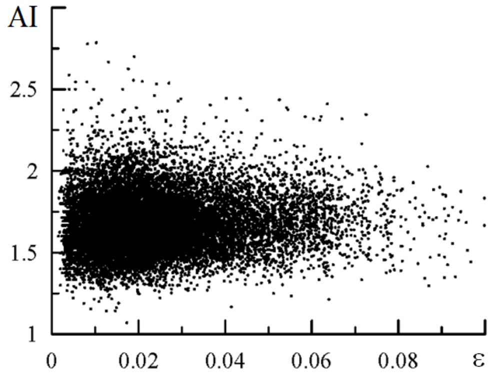


Fig. 2. Dependence of the abnormality index AI on the steepness ε

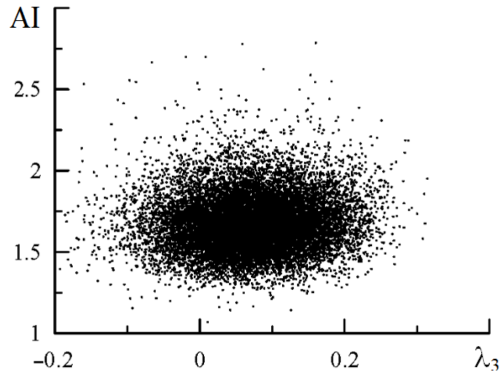


Fig. 3. Dependence of the abnormality index AI on the skewness λ_3

of nonlinearity [3]. For a random variable ξ with zero mean, the skewness is as follows

$$\lambda_3 = \overline{\xi^3} \big/ \overline{\xi^2}^{3/2},$$

where the overbar means averaging.

The correlation between the abnormality index and the skewness is shown in Fig. 3. The correlation coefficient between AI and λ_3 makes 0.06.

Within the framework of the analysis of various physical mechanisms, a number of theoretical works showed that an increase in the excess kurtosis should lead to an increase in the probability of the appearance of abnormal waves [5, 20]. The excess kurtosis is as follows

$$\lambda_4 = \overline{\xi^4} \big/ \overline{\xi^2}^{2} - 3.$$

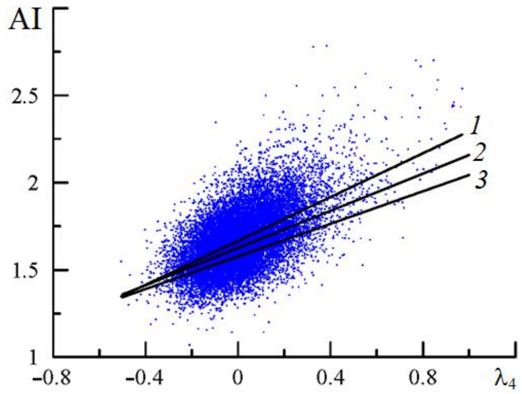


Fig. 4. Dependence of the abnormality index AI on the excess kurtosis λ_4. Lines 1–3 correspond to regressions (2)–(4)

As Fig. 4 shows, the general trend is the AI growth with the increase of λ_4. The correlation coefficient between AI and λ_4 makes 0.57. The linear regression describing the dependence of the AI index on the excess kurtosis, has the following form

$$\mathrm{AI} = 0.628\,\lambda_4 + 1.665\,. \quad (2)$$

The standard deviation makes 0.10. In previous studies, the following close regression dependences were obtained:

in [13]

$$\mathrm{AI} = 0.533\lambda_4 + 1.625 \quad (3)$$

and in [10]

$$\mathrm{AI} = 0.467\lambda_4 + 1.577\ . \quad (4)$$

The dependence of the AI index on λ_4 was also observed in a storm in the Black Sea studied in detail (autumn 2009) [21].

Thus, of three parameters considered here (ε, λ_3, λ_4), only the excess kurtosis is statistically related to the abnormality index.

Correlation of the abnormality index with the height of the wave crest

Along with the condition $\mathrm{AI} > 2$ to identify the abnormal waves, condition [12] is sometimes used

$$\mathrm{CI} = C_{\max} / H_S > 1.25\,, \quad (5)$$

where $C_{\max}$ – maximum crest height. The crest height is defined as the highest point on the wave line for the period between two consecutive crossings of the mean water level from bottom to top and from top to bottom [6].

The dependences of the CI index on the parameters characterizing the wave nonlinearity are shown in Fig. 5. For the calculations, the same data array was used as for the AI calculations. The correlation coefficients between CI and ε, λ_3, λ_4 make 0.09, 0.13 and 0.49, correspondingly. The dependence

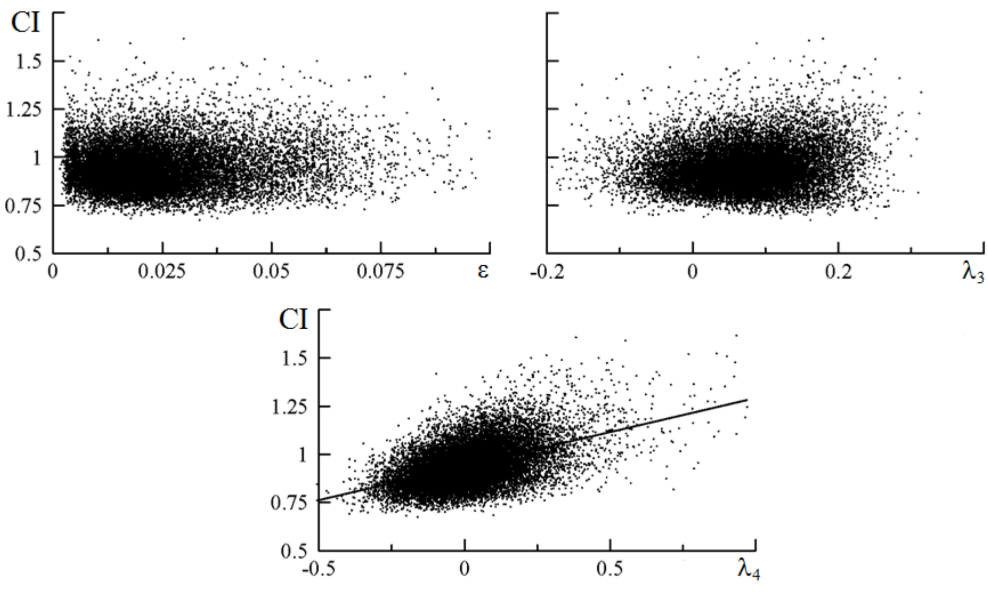
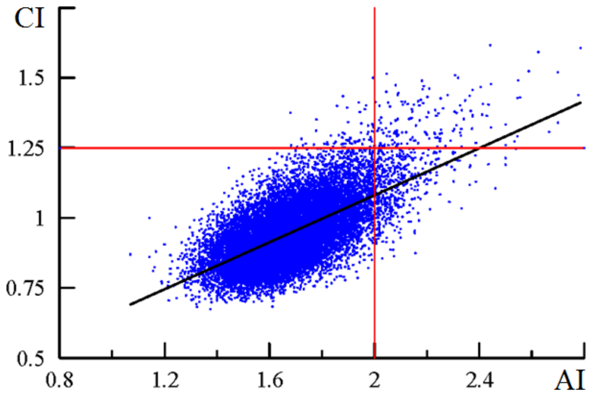


Fig. 5. Dependencies of the index CI on the parameters ε, λ_3 and λ_4. The line on the lower fragment corresponds to regression (6)



F i g . 6 . Interrelation of indices AI and CI. The red lines show the critical values of the indices, above which the wave is considered abnormal, the black line is the regression (7)

of CI on λ_4 can be approximated by the following linear regression

$$\mathrm{CI} = 0.353\lambda_4 + 0.939\,, \tag{6}$$

with standard deviation equal to 0.10.

Let us consider the relationship between AI and CI indices, which is shown in Fig. 6. The correlation coefficient between these indices makes 0.64. The relationship between AI and CI indices is described by the following linear regression

$$\mathrm{CI} = 0.42\mathrm{AI} + 0.241 \tag{7}$$

with standard deviation equal to 0.085.

Let us compare the probability of occurrence of abnormal waves determined in accordance with criteria (1) and (5). The number of points above the horizontal red line in Fig. 6 is noticeably smaller than those lying to the right of the vertical red line. This means that the probability of the appearance of an abnormal wave in accordance with criterion (5) (it will be denoted as P_C) is less than that with criterion (1). For the data array analyzed here, P_C = 1.3 % and P_A = 3.3 %.

Such a discrepancy in the estimates of the probability of the appearance of abnormal waves can be explained as follows. By the analogy with the determination of the crest height, we define the depth of the trough as the distance from the average water level to the lowest point on the wave profile for the period between two successive crossings of the average level from top to bottom and from bottom to top. There are three main forms of abnormal waves: positive, negative and sign-variable [11, 22]. Positive is the form in which the height of the crest is one and a half times more than the depth of the trough. Correspondingly, the form is negative, when the depth of the trough is one and a half times more than the height of the crest. The form with an intermediate ratio of the height of the crest and the depth of the trough is called sign-variable. According to the data of measurements in the coastal zone of the Baltic Sea (with the depth of 2.7 m), 63 % of abnormal waves had a positive form, 19.5 % had a sign-variable form, and 17.5 % had a negative form [22].

It should be noted that within the framework of the standard procedures for the calculation of the AI and CI indices, the characteristics of the largest of the abnormal waves are determined. This procedure does not take into account that several abnormal waves can take place during a measurement period.

Conclusion

Based on *in situ* wave measurements, the analysis was made concerning the appearance of abnormal waves in the coastal zone of the Black Sea. Two indices were used to identify abnormal waves. The first index is equal to the ratio of the maximum and significant wave heights AI, while the second index represents the ratio of the maximum crest height to the significant wave height CI.

It is shown that the AI and CI indices do not depend on the steepness of the waves and on the skewness of the sea surface elevations. A statistical correlation was found only for the excess kurtosis, which makes it possible to use it as a predictor in the problems on the forecast of the appearance of abnormal waves.

It is also shown that the probability of appearance of abnormal waves calculated on the basis of the AI index is higher than that calculated on the basis of the CI index. This is explained by the fact that there are three forms of abnormal waves, which are identified by different correlation of the height of the crest and the depth of the trough. The CI index allows distinguishing effectively only abnormal waves with their height of the crest greater than the depth of the trough.

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Alexander S. Zapevalov – problem statement, data processing and analysis, article text and graphic materials preparation

Anton V. Garmashov – data processing and analysis, analysis of literary sources

All the authors have read and approved the final manuscript.