Skewness and Kurtosis of the Surface Wave in the Coastal Zone of the Black Sea

A. S. Zapevalov ✉, A. V. Garmashov

Marine Hydrophysical Institute of RAS, Sevastopol, Russian Federation
✉ *sevzepter@mail.ru*

Purpose. The aim of the study is to analyze variability of the statistical moments characterizing deviations of the sea surface elevation distributions from the Gaussian.

Methods and Results. Field studies of the sea waves' characteristics were carried out from the stationary oceanographic platform located in the Black Sea near the Southern coast of Crimea. The data obtained both in summer and winter, were used. The statistical moments were calculated separately for wind waves and swell. The measurements were performed in a wide range of meteorological conditions and wave parameters (wind speed varied from 0 to 26 m/s, wave age – from 0 to 5.2 and steepness – from 0.005 to 0.095). For wind waves, the coefficients of skewness correlation with the waves' steepness and age were equal to 0.46 and 0.38. The kurtosis correlation coefficients with these parameters were small (0.09 and 0.07), but with the confidence level 99.8% – significant. For swell, the correlation coefficients were 1.5 – 2.0 times lower.

Conclusions. The statistical moments of the sea surface elevations of the third and higher orders are the indicators of the wave field nonlinearity, which should be taken into account when solving a wide range of the applied and fundamental problems. The deviations of the surface elevation distributions from the Gaussian one are not described unambiguously by the steepness and wave age. At the fixed values of these parameters, a large scatter in the skewness and kurtosis of the surface elevations is observed. This imposes significant limitations on the possibility of applying the nonlinear wave models based on the wave profile expansion by small parameter (steepness) degrees, in engineering calculations.

Keywords: sea surface, wind waves, swells, skewness, kurtosis, stationary oceanographic platform, Black Sea

Introduction

It is customary to distinguish the two types of sea waves nonlinearity: statistical nonlinearity arising in the presence of bound wave components, and dynamic nonlinearity caused by resonant and quasi-resonant wave-wave interactions [1]. Both types of nonlinearity lead to the fact that the distribution of sea surface elevations deviates from the Gaussian distribution [2–4].

The nonlinearity of sea waves is weak, and the deviations of the sea surface elevations distribution from the Gaussian distribution are small [5, 6]. Despite their smallness, these deviations must be taken into account when calculating the impact

of waves on vessels, oil and gas production platforms and coastal structures [7, 8], they play an important role in the occurrence of abnormally large waves [9, 10]. Deviations from the Gaussian distribution must also be taken into account when analyzing the ocean remote sensing data [11, 12].

The third and higher cumulants of sea surface elevations can be used as parameters characterizing the nonlinearity of the wave field [13, 14]. Measurement of cumulants of the fifth order and higher in marine conditions is difficult, therefore, when constructing the probability density function of surface elevations, only cumulants of the third and fourth orders are used [15, 16]. Laboratory and field studies have shown that there are clear dependences of the sea surface elevations' cumulants on the steepness and the stage of the wave field development [6, 17, 18]. The existence of such dependences is confirmed by the modeling of nonlinear effects in the field of sea waves [4, 19].

The land and orography significantly affect wind fields, which, in its turn, directly affect the evolution of local wave fields [20–22]. For modeling and forecasting the wave climate in inland and marginal seas, testing the wave models, the information on the variability of local statistical characteristics of the surface waves are required [23].

The aim of this work is to analyze the variability of statistical parameters characterizing the deviations of the distributions of sea surface elevations from the Gaussian distribution in the Black Sea coastal zone.

Instrumentation and measurement conditions

The measurements were carried out on a stationary oceanographic platform located in the coastal part of the Black Sea off the Southern Coast of Crimea. The platform is a rectangular pile structure with horizontal dimensions of 20×20 m. The sea depth at the point where the platform is installed is about ~ 30 m. The upper deck, on which the laboratory rooms are situated, is located at a height of 12 m, the height of the deck superstructures is 3 m.

For the waveform measurements, a resistive wave recorder, the sensor of which is a nichrome string, wound with a constant pitch on a carrying strength-power-communications cable. In order to minimize the disturbances of the wave field created by the platform supports, the wave recorder was positioned on a boom of 6 m. Wind velocity measurements were carried out from a mast installed in the middle of the deck superstructure. The wind velocity and direction sensors were located at 21 m height. The description and characteristics of the measuring equipment are presented in [24]. The reduction of the wind velocity measured at 21 m height to 10 height accepted in meteorology was carried out according to the standard method under the assumption of a logarithmic profile [25].

The measurements were carried out in June and December 2018, as well as in January 2019. The wind velocity during the measurement period varied within 0–26 m/s, the age of the waves was 0–5.2, and the steepness was 0.005–0.095. For the analysis, the characteristics of the surface wave field averaged over 20 min, as well as the characteristics of the wind velocity field, obtained simultaneously with the same averaging period, are used. The total data volume is more than 6500 measurement sessions.

Cumulants of the sea surface elevations

We will consider a uniform stationary wave field in which the surface elevation at a fixed point is described by a random function with zero mean value $\eta = \eta(t)$, where t is time. Distribution moments of order n are described by the expression

$$m_n = \int_{-\infty}^{\infty} \eta^n P(\eta) dx,$$

where $P(\eta)$ – is a function of probability density functions. The first four cumulants are associated with the statistical moments by the relation

$$\left. \begin{array}{l} \lambda_1 = m_1 = 0, \\ \lambda_2 = m_2, \\ \lambda_3 = m_3, \\ \lambda_4 = m_4 - 3m_2^2. \end{array} \right\}$$

For the Gaussian distribution

$$\left. \begin{array}{l} m_{2n} = (2n-1)!!\, m_2^n, \\ m_{2n+1} = 0, \quad n \geq 1, \end{array} \right\}$$

$$\left. \begin{array}{l} \lambda_2 = m_2, \\ \lambda_n = 0, \quad n > 2. \end{array} \right\}$$

The equality to zero of cumulants senior than the second order makes them convenient for the analysis of nonlinear effects in the field of the sea surface waves [13, 14]. When analyzing the data of field measurements, the asymmetry and kurtosis of the distribution of the sea surface elevations $\tilde{\lambda}_3 = m_3 / m_2^{3/2}$ and $\tilde{\lambda}_4 = m_4 / m_2^2 - 3$ are used.

We will use two dimensionless parameters as ones characterizing the evolution of the wave field. The first is the wave steepness

$$\varepsilon = m_2^{1/2} k_0,$$

where k_0 is the wave number of the wave spectrum peak. In what follows, the waves with k_0 wavenumber will be called dominant. Dominant waves belong to the type of gravitational waves, for which the dispersion relation $\omega^2 = g k$ is valid in deep water, whence it follows

$$\varepsilon = m_2^{1/2} \omega_0^2 / g,$$

where ω_0 is a frequency of dominant waves; g is a gravitational acceleration.

The deviation of the elevation distribution from the Gaussian distribution is also caused by the interaction of wind and waves. Obviously, the nature of the interaction will be different in the following stages: developing waves, fully developed waves, and swell. In what follows, we will use the parameter characterizing the age of the waves in the form

$$\zeta = U_{10}/C_0 \,,$$

where U_{10} is a wind velocity at 10 m height; C_0 is a phase velocity of dominant waves [26, 27]. In the laboratory measurements a similar parameter $\zeta^* = u_*/C_0$, where u_* is a dynamic velocity [17], is used. The higher values of ζ (or ζ^*) correspond to the earlier stages of the wind field development.

The location of the platform at a relatively small distance from the coast made it possible to measure the wave characteristics at the early stages of $\zeta > 2$ wave field development, which is difficult to carry out in the open sea conditions. The early stages of development correspond to the situation when the wind blows from the coast. However, it should be taken into account that the structure of the near-water boundary layer changes with the wind from the coast, and turbulent eddies formed over the land have a significant effect on it [21].

We will consider two situations: when the wave field is formed by the wind waves and when it is formed by the swell. The swell is almost always observed on the sea surface, therefore this division is conditional. It is true insofar as the energy of the wind waves and swell differs. Completely developed field of surface waves corresponds to $\zeta_0 = 0.83$, at $\zeta > \zeta_0$ we will conventionally consider the waves to be the wind ones, at $\zeta < \zeta_0$ – the swell.
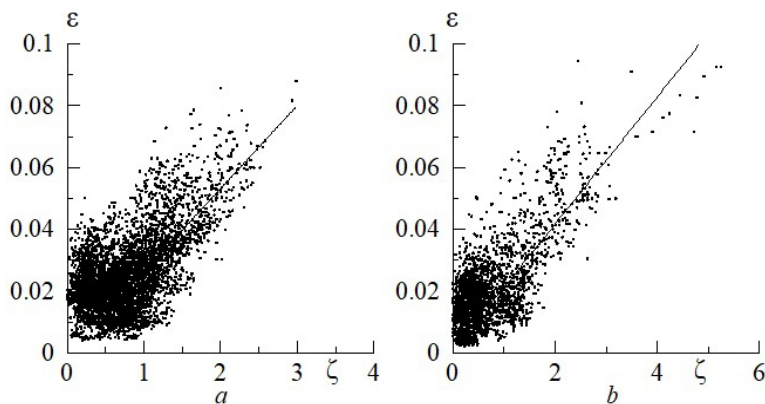

F i g. 1. Dependencies $\varepsilon = \varepsilon(\zeta)$ in the summer (*a*) and winter (*b*) periods

Variation of the wave steepness at different stages of the wave field development in winter and summer periods are presented in Fig. 1. Dependencies $\varepsilon = \varepsilon(\zeta)$ in the indicated periods are similar. The difference lies in the fact that in

summer with the wind blowing from the coast, the range of ζ parameter variation is much wider than in winter.

For wind waves, the relationship between the parameters ε and ζ, plotted over the entire data set obtained in different periods, is approximated by the expression

$$\varepsilon = 0.021\zeta,$$

The coefficient of correlation between ε and ζ is equal to $r(\varepsilon,\zeta) = 0.65$. For the swell

$$\varepsilon = 0.016 + 0.0061\zeta$$

and $r(\varepsilon,\zeta) = 0.15$.

Different nature of the relationship between the parameters ε and ζ, which determine the deviations from the Gaussian distribution, indicates the need to analyze the variability of cumulants $\tilde{\lambda}_3$ and $\tilde{\lambda}_4$ separately for wind waves and swell.

Skewness

We begin the analysis of deviations from the Gaussian distribution by studying the dependence of skewness on the steepness and age of waves, these dependences are given in Fig. 2. The values of skewness mainly vary within the range of – 0.05…0.3. These limits are close to the boundaries of $\tilde{\lambda}_3$ variation within the range of – 0.05…0.4, recorded during the measurements carried out at the Ekofisk platform, located in the North Sea at ~ 70 m depth [16]. According to our measurements and measurements from the Ekofisk platform, the lower boundary of $\tilde{\lambda}_3$ variation lies in the negative area. This means that, in contrast to the classical representation of the sea wave (a pointed crest and a shallow depression), in some situations the reverse structure is observed. The values $\tilde{\lambda}_3 < 0$ were also obtained during the experiments in a research facility at low steepness [17].

The statistical characteristics of $\tilde{\lambda}_3$ relationship with the parameters describing the steepness and age of the waves, ε and ζ, are given in Table. 1, where r is the correlation coefficient between $\tilde{\lambda}_3$ and the parameters ε and ζ; SD is a standard deviation. It also presents the coefficients of linear regressions $\tilde{\lambda}_3 = a + b\varepsilon$ and $\tilde{\lambda}_3 = a + b\zeta$ presented in Fig. 2. Statistical assessments lead to the following conclusions. The correlation coefficients between both $\tilde{\lambda}_3$ and parameters ε and ζ for the wind waves are higher than for the swell waves. The steepness variations have a greater effect on the shape of the distribution of sea surface elevations than the wave age variations.
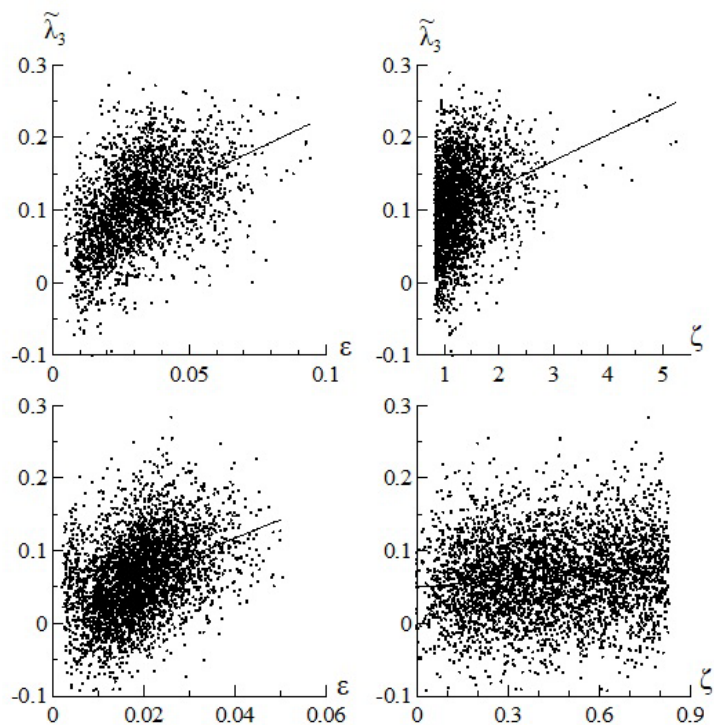
F i g. 2. Dependences of skewness $\tilde{\lambda}_3$ on the steepness ε and wave age ζ (the upper row – wind waves, the lower one – swell; points are measurement data, lines are regressions)

T a b l e 1

Statistical characteristics describing the skewness $\tilde{\lambda}_3$ dependences on the steepness ε and wave age ζ

Parameters	Coefficients			SD
	r	a	b	
For wind waves				
ε	0.46	0.050	1.795	0.052
ζ	0.28	0.061	0.036	0.056
For swell				
ε	0.38	0.016	2.547	0.051
ζ	0.13	0.049	0.035	0.055

Kurtosis

The kurtosis dependences on the steepness and stage of wave development are shown in Fig. 3. The kurtosis values for wind waves mainly vary within the range of – 0.4...0.4, which coincides with its variation limits obtained from

the measurements on the Ekofisk platform [16]. Statistical characteristics describing the relationship of $\tilde{\lambda}_4$ and parameters ε and ζ are given in Table 2. The structure and designations in Table 2 and Table 1 are similar.
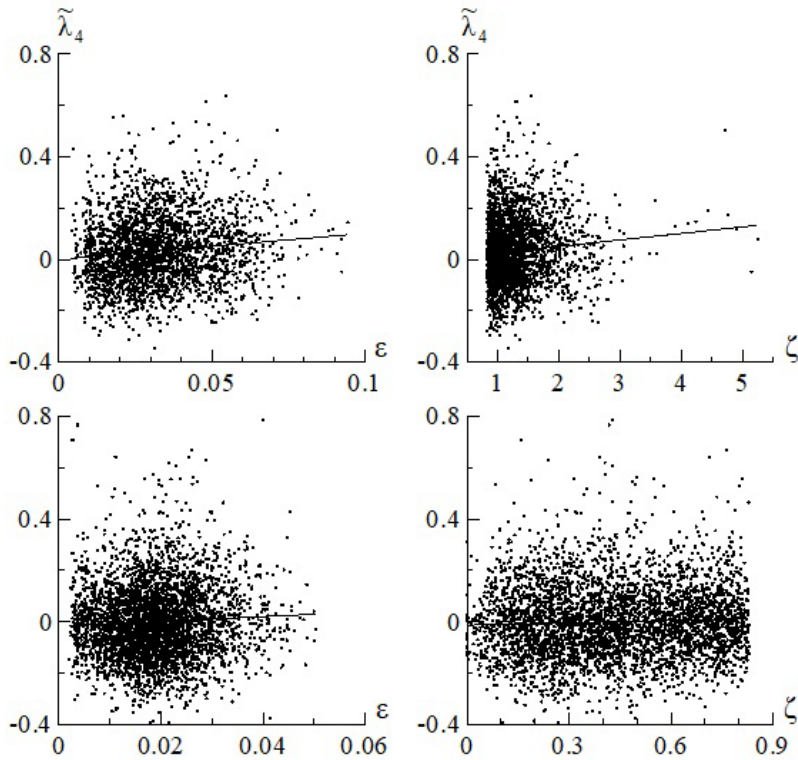

F i g. 3. Dependences of the kurtosis $\tilde{\lambda}_4$ on the steepness ε and wave age ζ (the upper row – wind waves, the lower one – swell; points are measurement data, lines are regressions)

The coefficients of correlation between $\tilde{\lambda}_4$ and the parameters ε and ζ are small, which determines the need to test the hypothesis that they are equal to zero. Evaluation based on the Student's test showed that for the wind waves with a probability of 99.8%, the correlation coefficients $r(\tilde{\lambda}_4, \varepsilon)$ and $r(\tilde{\lambda}_4, \zeta)$ are significant. For swell waves, the correlation coefficient $r(\tilde{\lambda}_4, \varepsilon)$ is significant with a probability of 95%, and the correlation coefficient $r(\tilde{\lambda}_4, \zeta)$ is significant with a probability of 90%.

The studies of senior cumulants from the third to eighth order, carried out in the tray, showed that all cumulants depend on the steepness of the waves [17]. The exception was the fourth-order cumulant ($\tilde{\lambda}_4$), for which no dependence was found.

Statistical characteristics describing the kurtosis $\tilde{\lambda}_4$ dependences on the steepness ε and wave age ζ

Parameters	Coefficients			SD
	r	a	b	
For wind waves				
ε	0.09	0.006	0.865	0.14
ζ	0.07	0.005	0.022	0.14
For swell				
ε	0.05	–0.016	0.881	0.15
ζ	0.04	–0.012	0.030	0.15

Discussion

In recent years, in the analysis and forecasting of the sea surface waves, second-order nonlinear models based on the wave profile decomposition in a series in powers of a junior parameter ε have become widespread [8, 14, 16, 19]. In these models, elevation is represented as the sum of the linear and non-linear components. The linear component is a superposition of sinusoidal waves:

$$\eta_L(x,t) = \sum_{n=1}^{\infty} a_n \cos\psi_n,$$

where x is a spatial coordinate; a_n is an amplitude; $\psi_n = k_n x - \omega_n t + \varphi_n$, k_n and ω_n are wave number and angular frequency, φ_n is a phase. Nonlinear component is described by the equation

$$\eta_N(x,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\left\{ a_n a_n \left[B_{mn}^{-} \cos(\psi_m - \psi_n) + B_{mn}^{+} \cos(\psi_m + \psi_n) \right] \right\}, \qquad (1)$$

where B_{mn}^{-} and B_{mn}^{+} are the transfer functions of the second order, which are calculated from the Laplace equation for the velocity potential with nonlinear boundary conditions [16]. The nonlinear model takes into account the bound second-order components that appear as a result of the interaction of free waves.

The form of the probability density functions of the surface elevations constructed within the framework of the nonlinear model (1) depends only on one parameter – the steepness. Accordingly, the cumulants of the surface elevations are single-valued functions of the steepness, while from the measurement data (see Figs. 2 and 3) it follows that at the same ε the values of $\tilde{\lambda}_3$ and $\tilde{\lambda}_4$ can differ significantly. Nonlinear models describe only the average trends in cumulant changes with a steepness variation, but do not allow describing the whole variety of situations that arise in marine conditions. Perhaps this is one of the reasons due to which these models have not become widespread in engineering calculations.

As shown above, the statistical characteristics describing the relationship between the steepness and cumulants $\tilde{\lambda}_3$ and $\tilde{\lambda}_4$ are somewhat different for the wind waves and swell. We are to consider which situation is closer to the theoretical values of the cumulants obtained within the framework of the second-order nonlinear model. For comparison, we will use the analytical dependences given in [19]:

$$\tilde{\lambda}_3{}^N = 3\varepsilon + O(\varepsilon^3),\tag{2}$$

$$\tilde{\lambda}_4{}^N = 12\varepsilon^2 + O(\varepsilon^4),\tag{3}$$

where the superscript N means that the cumulant is calculated using a nonlinear model. The results of comparison of theoretical and measured cumulants are demonstrated in Fig. 4. It can be seen that for the wind waves with increasing steepness, the values $\tilde{\lambda}_3{}^N$ grow faster than $\tilde{\lambda}_3$. For $\varepsilon > 0.08$, the values of $\tilde{\lambda}_3{}^N$ go beyond the upper boundary of the region corresponding to the standard deviation from the regression. For the swell, the growth rates $\tilde{\lambda}_3{}^N$ and $\tilde{\lambda}_3$ are approximately equal, the coefficients at ε in equation (2) and in the linear regression equation differ by 20%. The dependences $\tilde{\lambda}_4{}^N = \tilde{\lambda}_4{}^N(\varepsilon)$ and linear regressions $\tilde{\lambda}_4 = \tilde{\lambda}_4(\varepsilon)$ for both wind waves and swell are close to each other.
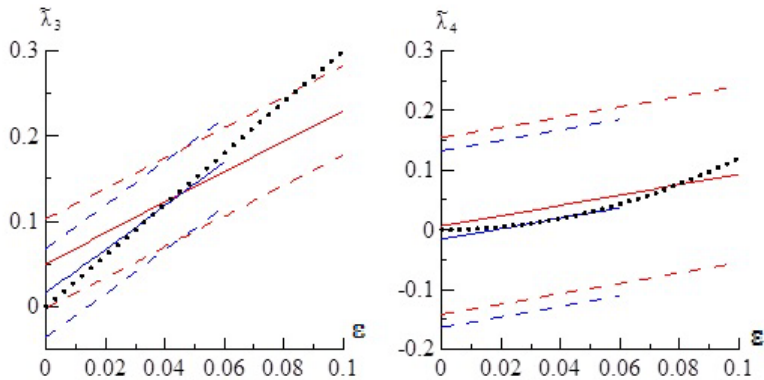

F i g. 4. Theoretical and measured dependences of the cumulants $\tilde{\lambda}_3$ and $\tilde{\lambda}_4$ on the waves' steepness ε (red color shows the dependences obtained for wind waves, blue color – for swell; solid lines are the linear regressions, dashed ones denote STD; dotted line shows the dependencies (2) and (3), respectively)

Conclusion

Based on the data of direct wave measurements, an analysis of the deviations of the sea surface elevations' distributions from the Gaussian distribution is carried out. The measurements were carried out in summer and winter seasons in a wide range of variations in meteorological conditions and wave parameters (wind velocity varied within the range of 0–26 m/s, wave age 0–5.2, and steepness 0.005–0.095).

It was revealed that for the wind waves the correlation coefficients of the of the steepness kurtosis and the wave age kurtosis are equal to 0.46 and 0.38. The kurtosis correlation coefficients with these parameters are small (0.09 and 0.07), but they are significant with a confidence level of 99.8%. For the swell, the correlation coefficients are approximately one and a half to two times lower, $r(\tilde{\lambda}_3, \varepsilon) = 0.38$, $r(\tilde{\lambda}_3, \zeta) = 0.13$, $r(\tilde{\lambda}_4, \varepsilon) = 0.05$, $r(\tilde{\lambda}_4, \zeta) = 0.04$. The coefficients $r(\tilde{\lambda}_4, \varepsilon)$ and $r(\tilde{\lambda}_4, \zeta)$ are significant with a confidence level of 95 and 90%, respectively.

It is concluded that the deviations of the surface elevations' distribution from the Gaussian distribution are not uniquely described by the steepness and age of the waves. At the fixed values of the steepness or the wave age, a large scatter in $\tilde{\lambda}_3$ and $\tilde{\lambda}_4$ values is observed. This imposes significant restrictions on the possibility of using nonlinear wave models (in particular, model (1)) based on the wave profile decomposition in powers of a small parameter (steepness) in engineering calculations.

The measurement data analyzed in this work were obtained in situations when the waves got at the measurement point both from the open sea and from the coast, i.e. under different wave formation conditions. The sea depth at the point where the measurements were taken corresponds to the "deep water" condition. This suggests that the conclusions drawn in this work will be true for other water areas as well.

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About the authors:

Aleksandr S. Zapevalov, Chief Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya str., Sevastopol, 299011, Russian Federation), Dr. Sci. (Phys.-Math.), **Scopus Author ID: 7004433476**, **WoS ResearcherID: V-7880-2017**, sevzepter@mail.ru

Anton V. Garmashov, Senior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya str., Sevastopol, 299011, Russian Federation), Ph. D. (Geogr.), **Scopus Author ID: 54924806400**, **WoS ResearcherID: P-4155-2017**, ant.gar@mail.ru

Contribution of the co-authors:

Aleksandr S. Zapevalov – formulation of goals and objectives of the study; development of a statistical model; preparation of the paper text; editing and supplementing the paper text

Anton V. Garmashov – correcting the statistical model and carrying out the calculations; formalized and non-formalized data analysis; analysis and generalization of the research results

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