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A SIMPLE STOCHASTIC MODEL OF NATURAL RHYTHMIC PROCESSES

by

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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A SIMPLE STOCHASTIC MODEL OF NATURAL RHYTHMIC PROCESSES

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L'vov

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The investigation of biological, meteorological, acoustic, etc. phenomena within the framework of biological clocks, the perception of external information by living systems, physics of the atmosphere, and statistical methods of predicting the weather, etc. require the analyzing of processes which are of a complex random nature. As is known, the linear theory describes such processes with correlation functions and mathematical expectations. For determining them the averaging should be based on distributions, which as a rule are unknown, or in practice we have only segments of a limited number of realizations or one unique realization. In this case it is possible to calculate, as an example, by the method of moving averaging, the estimates of mathematical expectations, correlation functions and harmonic components. For this the methods of the theory of stationary processes are used, and also the concepts, which within the framework of that theory have a natural interpretation. In particular, the operator of moving averaging in the theory of stationary processes is invariant, i.e., it converts a stationary process into stationary.

However, the mentioned processes which actually exist in nature in the majority of cases have a nonstationary rhythmic nature, as a result of which the need arises for matching methods, developed for analyzing stationary processes, with the characteristics of the phenomena being studied. Many authors, Solberger [1], Romanenko and Sergeyev [13] in particular, note that it is not to the purpose to use these methods for such essentially nonstationary processes as these - biological rhythms for example. Therefore it is necessary to develop methods which are based on the properties namely of these nonstationary processes. It is necessary that the statistical methods recommended by natural science investigators have a simple interpretation in terms of the concepts of the science which encompasses the area of their investigations.

It is advisable that the statistical analysis of a complex phenomenon begin with the development of the appropriate model, since the direct application of the so-called classical methods (statistical methods of random variables), which do not correspond to the essence of the phenomena being investigated, gives very inaccurate results, the interpretation of which is completely unsatisfactory [10, 14]. Pitendray (see [1]) points out that such models may be provided by specialists in applied physics and mathematics, who will require the most significant of the known factors concerning the natural processes being studied.

This motivates the necessity of substantiating a simple mathematical model of natural rhythmic processes as the basis for developing methods of their statistical analysis and the interpretation of the results obtained.

The idea of developing the model which is proposed in this paper (describing only the periodic nature of one period; the superimposing of the rhythms of other periods in the experimental data is eliminated by the appropriate selection of the interval of the moving averaging) is that based on the most significant facts about natural rhythmic processes, known from the literature and obtained in investigations of the reactions to external factors on the part of certain organisms which can predict a change in weather, to establish the general regularity in the class of random processes which describe rhythmic phenomena, which would make it possible to identify the processes under study by means of an experimental determination (based on realization) of the estimates of their characteristics. Here it is understood that the characteristics and the methods of determining them should have a natural interpretation within the framework of the model.

As a rule the tracings of rhythmic phenomena which are obtained experimentally have a "noise-like" nature. This means that they cannot be predetermined even with the help of a complex analytical expression, one can only speak of the probabilistic characteristics of the entire set, i.e., to consider a random process, the realization of which they are. From here follows the first feature of the model - it should be a random (stochastic) process.

Experimentally the noisy nature is demonstrated by the fact that with an increase in the frequency of the readings the new values of realization do not lie on a smooth curve, which connects the values obtained at a lesser frequency of readings, but display an irregular structure of a higher order. Figure 1 shows the intensities (in relative units) of the motor activity of groundlings (*Misgurnus fossilis* L.), determined over a period of 5 min once a day (a), every hour (b), and every 10 min (c).

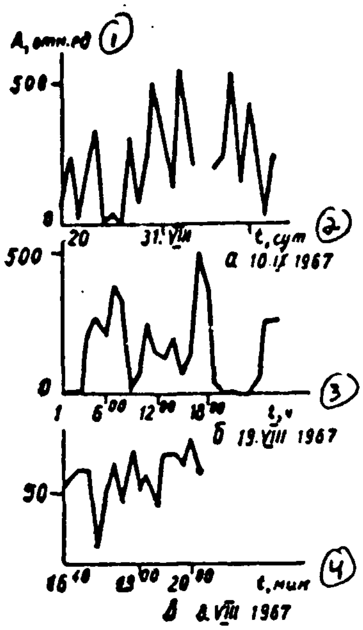

Figure 1. Examples of realizations of intensity of motor activity of groundlings at different frequencies of readings.
Key: (1) relative units; (2) t, days; (3) t, hours; (4) t, min.

A specific periodic nature is observed in rhythmic phenomena, therefore naturally a question arises concerning its expansion into simple harmonic components. A classical analysis of time series, in an analogy with the study of tides and variable stars, rests on concepts of the presence of discrete harmonic components in the tracings and the attempt to connect them with the action of certain periodic causes: each period has its own cause [17]. If these methods are applied to phenomena which do not have such properties, but represent a specific type of noise, where all frequencies, even those the total energy of which is negligible [7, 16], have a noticeable influence on the nature of the phenomenon, then they lead to misunderstandings and inaccurate results, since in a number of cases low-energy components cause significant aftereffects. For example, it is shown in [6] that disregard of weak gravitational waves in models of numerical prediction entails errors, since the superpositioning of these waves can be the cause of development of a nongeostrophic situation which exerts a considerable influence on the process of weather formation.

Consequently, in the study of rhythmic phenomena it is necessary to consider random processes, which permit expansion into harmonics, the frequencies of which in a general case have a continuous spectrum. For stationary processes such an expansion is made simply; its correlation function $R_\xi(u)=E\xi(t+u)\overline{\xi(t)}$ is the derivative, averaged with respect to distribution, of values of the process $\xi(\cdot)$ at the moments (t+u) and t. It depends only on the shift and based on the Wiener-Khinchin theorem is a Fourier-transform from the spectral function $F(\lambda)$, increases of which give the dispersions of the harmonics of the process: $R_\xi(u)=\int_{-\infty}^{\infty} e^{iu\lambda}\,dF(\lambda)$. The harmonics here are uncorrelated. However, rhythmic phenomena are essentially nonstationary, therefore for their model it is necessary to take a process with that class of nonstationary for which harmonic expansion makes sense. This class should be characterized either through the properties of the correlation function $r(s, t)=E\xi(s)\overline{\xi(t)}$, this time already dependent on two variables - the moments of the averaged values of the process, or through the properties of its two-dimensional Fourier-transform.

Since from the point of view of exposing the periodic nature in the structure of the process harmonic analysis has a simpler interpretation and produces more valuable information in comparison with the information supplied by the correlation function [16], then it is natural to begin the characterization of the class of processes of the harmonic expansion of their realizations. Keeping in mind that the simplest processes, having the representation

$$\xi(t)=\int_{-\infty}^{\infty} e^{it\lambda}d\zeta(\lambda) \qquad (1)$$

in the form of the superposition of harmonics, the amplitude and phase of which are determined respectively by the modulus and argument of increases of random spectral measures $d\zeta(\lambda)$, will be harmonized processes [9], it is natural to assume that the model of a rhythmic phenomenon should be one of such processes.

From formula (1) follows the harmonizability of the correlation function of the process, i.e., the validity of its representation in the form

$$r_\xi(s,t)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{i(s\lambda-t\mu)}d\lambda d\mu S(\lambda,\mu). \qquad (2)$$

If the two-frequency spectral function $S(\lambda,\mu)$ is differentiable for both arguments (which is always valid, at least in the sense of the theory of generalized functions), then the derivative $s(\lambda, \mu) = \frac{\partial^2 s(\lambda, \mu)}{\partial\lambda\partial\mu}$

characterizes the correlation of the harmonics with frequencies λ and μ. In particular for a stationary process, since its harmonics are uncorrelated, this derivative will have the form: $s(\lambda, \mu) = f(\lambda)\delta(\lambda - \mu)$, where $f(\lambda)$ - spectral density of the process, and $\delta(\cdot)$ - δ - the Dirac function. Then the integral (2) transforms correspondingly into an integral of the form

$r(s, t) = \int_{-\infty}^{\infty} e^{i(s-t)\lambda} f(\lambda)\, d\lambda = R_\xi(s-t)$. If the substitution of s=t+u is made and for the characteristic of the correlation bond of the values of the process the new function

$$b_\xi(t, u) = r_\xi(t + u, t), \tag{3}$$

is introduced, then for the stationary process we obtain

$$b_\xi(t, u) = \int_{-\infty}^{\infty} e^{iu\lambda} f(\lambda)\, d\lambda = R_\xi(u), \tag{4}$$

from which it follows that the function $b_\xi(t, u)$ for a stationary process in the case of all u does not depend on t. Thus the dependence of the function of correlation $b_\xi(t, u)$ on t can serve as an indicator of the nonstationary nature of the process. Having placed u=0 in formulas (3) and (4), the result is that such an indicator will be the dispersion of the process

$$\sigma_\xi^2(t) = b_\xi(t, 0), \tag{5}$$

constant for a stationary process: $\sigma_\xi^2(t) = R_\xi(0)$.

Introducing the representation (also in the sense of the theory of generalized functions) $b_\xi(t, u) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{i(u\lambda - t\nu)} f(\lambda, \nu)\, d\lambda d\nu$, for the function of the correlation bond of the harmonics we obtain

$$s(\lambda, \mu) = f(\lambda, \mu - \lambda). \tag{6}$$

The third important feature of rhythmic phenomena is a form of t' ir realizations which is close to amplitude-modulated random processes [18]. This makes it possible to require that for a model of such oscillations the dispersion, and, according to formula (5), the function of correlation $b_\xi(\cdot, u)$ be periodic functions of time. The latter property uniquely determines the class of random functions, since it is a characteristic for periodically correlated processes, although the period of correlativity is not determined uniquely by the period of dispersion.

Also for the indicated processes, according to the determination in [8] the mathematical expectation will be periodic with the same period, i.e., $m_\xi(t+T)=m_\xi(t)$, $b_\xi(t+T, u)=b_\xi(t, u)$ with all i and u. Then for such a model the correlation function has the form

$$b_\xi(t,u)=\sum_{k=-\infty}^{\infty} e^{i\frac{2\pi}{T}kt} B_k(u), \tag{7}$$

where functions $B_k(\cdot)$ are called the correlation components. It follows from this formula [4] that the correlation function of the harmonics is determined through the spectral components of the process

$$f_k(\lambda)=\frac{1}{2\pi}\int_{-\infty}^{\infty} B_k(u)\, e^{-i\lambda u} du \tag{8}$$

by the correlation $s(\lambda,\mu)=\sum_{k=-\infty}^{\infty} f_k(\lambda)\,\delta\left(\mu-\lambda+k\frac{2\pi}{T}\right)$.

It is evident from the last formula that the harmonic of frequency λ_0 is correlated only with harmonics of frequency $\lambda_0 - k\frac{2\pi}{T}$ when $k=\overline{-\infty,\infty}$. The coefficients of correlation are determined by the spectral components ( ). On the other hand, the function $f_k(\cdot)$ is the k-th harmonic of change in spectral density of the current spectrum, which is evident from the representation of the correlation function through the current spectrum: $b_\xi(t,u)=\int_{-\infty}^{\infty} e^{iu\lambda} f(t,\lambda)\, d\lambda$; its change is periodic with a period equal to the period of correlativity of the process, since $f(t,\lambda)=\sum_{k=-\infty}^{\infty} f_k(\lambda)\, e^{ik\frac{2\pi}{T}t}$.

From such a type of correlativity of harmonics it follows that the filter, the half band width of which $\frac{\Delta\lambda}{2} < \frac{\pi}{T}$, makes it possible to eliminate the influence of harmonics which are correlated with filtered out. Therefore in this case all the results of the theory of filtration of stationary processes remain in force. It is not difficult to obtain the other properties of periodically correlated processes from its representation through stationary and stationary-correlated components [4] $\xi_k(t)$:

$$\xi(t) = \sum_{k=-\infty}^{\infty} \xi_k(t) e^{ik\frac{2\pi}{T}t}. \tag{9}$$

From here for the mathematical expectation we have $m_\xi(t) = \sum_{k=-\infty}^{\infty} m_k e^{ik\frac{2\pi}{T}t}$

where $m_k = E\xi_k(t)$, from which it follows that it can be zero in the case of centrality of the components (all $m_k=0$); a periodic function with a period equal to the period of correlativity of the process if all $m_k=0$; constant if $m_k=0$ with $k \neq 0$ and $m_0 \neq 0$.

The expression of dispersion $\sigma_\xi^2(t) = \sum_{k=-\infty}^{\infty} B_k(0) e^{i\frac{2\pi}{T}kt}$, obtained from formulas (6) and (7), shows that in a general case the dispersion is periodic of the same period as the period of correlativity; it may be periodic with a half period and it may be constant. If $B_{2p+1}(u) \equiv 0$ in the case of all u and all whole p, then the function of correlation will have a half period. And in order that the mathematical expectation would have the same period it is necessary that the odd components in formula (9) be centered, i.e., $E\xi_k(t)=0$. If $B_k(u)=0$ with all u and $k \neq 0$, and $B_0(u) \neq 0$, then the process degenerates into stationary relative to correlation.

When $B_0(u)=0$ it degenerates into a determinate function. And if the periodically correlated process is the result of the conversion of stationary with the help of a system with periodically changing parameters in a steady-state mode, then this process possesses a period of correlativity half that of the period of change in the parameters of the system.

Taking this into account, we arrive at the conclusion that the dispersion of a periodically correlated process is more informative than mathematical expectation, since it reflects the periodic nature of the structure of the process more deeply.

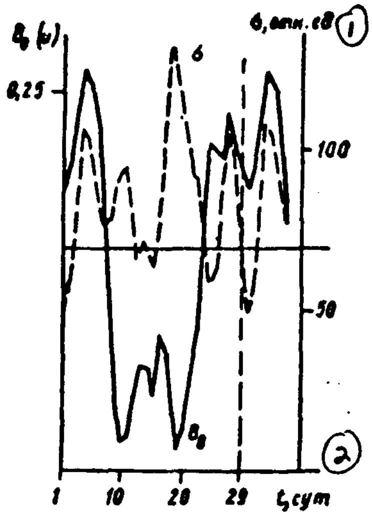

Figure 2. Change in the null correlation component ($B_0(u)$) and the dispersion (σ^2) of the motor activity of groundlings over the course of a month.
Key: (1) relative units; (2) t, days.

Since the period of mathematical expectation is determined by the centrality of stationary components, and the period of dispersion is determined by the values in the null of the correlation components, then all the mathematical expectation and dispersion can be used as independent criteria for the preliminary establishment of the precise period of correlativity of the process, although it is not determined uniquely. Also the null correlation component will be such a criterion when it is a periodic function. This criterion is independent of the previous, since the null correlation component does not have to be periodic, but in the case of periodicity its period is a multiple of the period of correlativity.

Figure 2 depicts the changes in the null component of the correlation function and dispersion over the course of a month, calculated based on the data of motor activity of groundlings during August-September 1968 [3] using the formula

$$B_0(u) = r(u) = \frac{\frac{1}{N}\sum_{k=1}^{N} \xi_k \xi_{k+u} - \frac{1}{N^2}\sum_{k=1}^{N} \xi_k \sum_{k=1}^{N} \xi_{k+u}}{\sigma_k \sigma_{k+u}}, \text{ где } \sigma_k^2 = \frac{1}{N}\sum_{k=1}^{N} (\xi_k - m_k)^2.$$

As is evident from the drawing, the bioactivity of groundlings is a nonstationary process with dispersion, having a period which is half that of the period of correlativity.

Since according to work [4] in formula (7) only $B_0(u)$ is a positively determined function, then $f_0(\lambda) \geqslant 0$ and this function characterizes the harmonics which make up the process, therefore in a physical sense it cannot be negative. The remaining correlation components $B_k(u)$ are not positively definite, therefore the spectral components $f_k(\lambda)$ when $k \neq 0$, generally speaking, will be complex, since they describe the correlation of different harmonics. A stationary process which has the same set of harmonics as a given nonstationary, and with the same dispersions, is called a stationary approximation of the latter [12].

Consequently a stationary approximation differs from the process itself by the absence of a correlation between harmonics. Its correlation function is determined [12, 15] by the expression $R(u) = \lim_{T \to \infty} \frac{1}{T} \int_{-\frac{T}{2}}^{\frac{T}{2}} b_\xi(t, u)\, dt$. It is demonstrated in work [4] that in this case $R(u)=B_0(u)$, i.e., the null correlation component in formula (7) determines the stationary approximation of the process.

For the statistical analysis of rhythmicality in processes of a different scale the need arises for their normalization (standardization), i.e., in place of $\xi(t)$ the following process is considered

$$\tilde{\xi}(t) = \frac{\xi(t) - m_\xi(t)}{\sigma_\xi(t)}.$$

For a normalized process $m_{\tilde{\xi}} = 0,\ \sigma_{\tilde{\xi}} = 1$, and the function of correlation $b_{\tilde{\xi}}(t, u) = \frac{b_\xi(t, u)}{\sigma_\xi(t+u)\,\sigma_\xi(t)}$ will always be periodic with respect to t, with a period equal to the period of correlativity, in other words, the periodic correlativity is invariant with respect to normalization [5].

Only for the case when a periodically correlated process has the nature of simple modulation, i.e., has the form

$$\xi(t) = \eta(t) f(t), \qquad (10)$$

where $\eta(t)$ - stationary process, and $f(t)$ - actual periodic function, after standardization we obtain a stationary process, since then $b_\xi(t, u) = \frac{R_\eta(u)}{\sigma_\eta^2} = \rho_\eta(u)$. The reason here lies in the fact that a process of form (10) belongs to a class of processes which are normalized (reducible) to stationary [11]. Consequently the reducibility of a periodically correlated process to stationary can serve as a characteristic sign of its affiliation to processes of the type of simple modulation.

In order to analyze the nature of the nonstationary state with a period of more than 24 hours in meteorological and biophysical phenomena, to evaluate the comparative biometeorological information content of mathematical expectation and dispersion, and also the influence of standardization of realizations of these processes, investigations were made of changes in atmospheric pressure * and the motor activity of groundlings over the period of time from 9 through 27 September 1965 with a frequency of sampling of one reading an hour [2].

* These measurements of atmospheric pressure were courteously made available to us by Yu.I. Bershchenskiy, head of the L'vov Weather Service.

Figure 3 shows (from the bottom up) segments of realization respectively of bioactivity (A) and atmospheric pressure (P), their moving average ($\bar{A}$, $\bar{P}$) and moving dispersions (σ_A^2, σ_P^2), and also the results of standardization of these realizations ($\Delta\bar{A}$ and $\Delta\bar{P}$). The interval of the moving average is equal to 25 h. Under the dispersions the wedges show the presence of precipitation at ten stations in the L'vovskaya Oblast, and the diamonds - the passage of fronts in the city of L'vov. The drawing shows the evident presence of a periodicity of the average and dispersion, both of bioactivity and atmospheric pressure with a period of seven-eight days (approximately half of the semimonthly rhythm, see Fig. 2), a greater prognostic biometeorological information content of dispersion with respect to precipitation, and also the invariability of the structure of periodicity of the investigated realization in the case of standardization. This shows that the realizations agree satisfactorily with the proposed model, however, are not always processes of the type of simple modulation, therefore the methods for investigating them are in need of further development.

Thus it is evident from the analysis made that the proposed model provides a natural description of the rhythmic nature of a random process, agreeing satisfactorily with data from investigations of natural rhythmic processes which are so diverse in their nature as the change in atmospheric pressure and bioactivity of groundlings, it substantiates the possibility of standardization of the results of measurements of the parameters of rhythmic phenomena and the application of modified classical methods for their analysis, it demonstrates the information content of mathematical expectation, the null correlation component and dispersion; also it represents a general model of rhythmic phenomena, including the known models:

additive - of the type of a periodic process on a background of stationary noise, and multiplicative - of the type of the process of simple modulation. The first of these is obtained if in formula (9) the stationary components are noncentered and noncorrelated, and the second - when any of the components is equal to a constant number, its own for each component, and multiplied by the same stationary process.

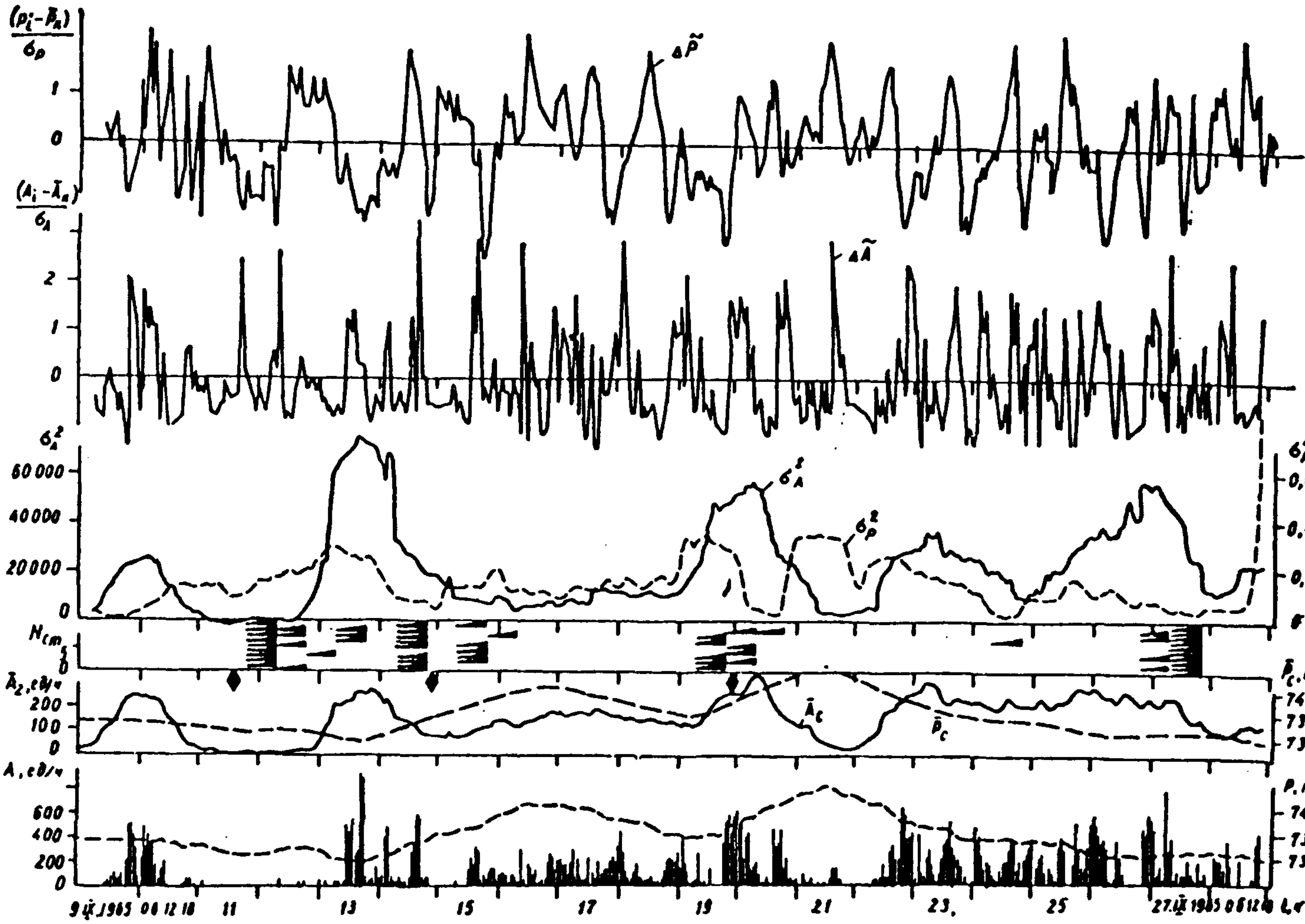

Figure 3. Results of measurements and processing of the bioactivity of groundlings and atmospheric pressure and their comparison with elements of weather.

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