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SCIENTIFIC COMMUNICATIONS

Analysis of the Spectral Matrices of Hydrogeological Observations at the Petropavlovsk Geodynamic Research Site, Kamchatka, and Their Comparison with the Seismic Regime

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INTRODUCTION

This paper is a continuation of the previous ones [1, 2] and presents the results of practical application of the multidimensional analysis of integrated geophysical data to hydrogeological monitoring data obtained at the Petropavlovsk geodynamic research site for 1986–1992. The analysis consists of constructing the frequency–time evolution diagrams for the maximum eigenvalue of the spectral matrices of the multidimensional time series with the goal of identifying the time intervals and frequency bands of the synchronous behavior of the scalar time series describing hydrodynamic and hydrogeochemical data from spaced boreholes and sources. It is suggested that the synchronization of variations in physical parameters obtained at different points of the survey network or measured at the same point may serve as a precursor of the preparing earthquake [1, 2].

In fact, this approach belongs to a class of statistical methods for lowering the dimension of data and determining the most general significant factors in a set of different multidimensional experimental data. Historically, the first method of this type was that of the principal components, which was initially developed to analyze the covariance matrices of data obtained in economics, psychology, and biology and resulted in the occurrence of the present factor analysis, which is widely applied in various fields, including the earth sciences [3]. Among these methods, there is a method of identifying a significant indication in pattern recognition with the use of the Karhunen–Loev expansion [4] and the method of orthogonal empirical functions employed in meteorology [5] and geomorphology [6]. Brillinger [7] suggested extending the method of principal components to the spectral analysis of multidimensional time series and applied it for joint analysis of the average monthly temperature series observed at 14 meteorological stations. A related approach is the construction of the spectral estimates with a high resolution in frequency and with the use of the eigenvalues and eigenvectors of the covariance matrix (methods of Pisarenko, MUSIC, and EV) [8].

METHOD OF DATA PROCESSING

The goal of multidimensional processing is to analyze the general relations between variations in hydrophysical and gas–hydrochemical parameters obtained from a network. Such an analysis enables us to detect a new signal (as compared with the common visual anomalies sought for in seismic regions)—enhancement in the synchronous or collective behavior of different hydrogeological regime indications of separate water seepages (holes, springs) or in different parameters measured in a single water seepage—and to establish the frequency bands and time intervals in which the synchronization takes place.

The visual analysis of graphs of variations in parameters allows us to mark specific features in a low-frequency range only. Furthermore, the visual analysis of a large number of graphs [for example, 10] is practically impossible and affected by the strong influence of subjective, human factors. At the same time, the proposed method enables us to make a uniform quantitative joint analysis of a reasonably arbitrary number of time series in any frequency range allowed by the scan frequency and sample length.

To identify the synchronization effect, Lyubushin [1, 2] suggested that the method of principal components in the frequency domain [7] be used. From the point of view of calculation, this method is an estimation of the maximum eigenvalue $\lambda_1(\omega)$ of the spectral matrix $S(\omega)$ in a band of frequency ω. The eigenvalue is the power spectrum of the first principal component of an initial multidimensional series, i.e., the scalar time series that may be obtained by linear filtration of the initial series and that bears the maximal information on the joint (synchronous) behavior of the scalar components of the initial vector series (the Gaussian time series) [7]. An increase in $\lambda_1(\omega)$ in certain frequency ranges implies an enhancement of the synchronous behavior of the harmonic components in these ranges for all of the scalar components of the initial time series.

Estimating the maximum eigenvalue $\lambda_1(\omega)$ of the spectral matrix $S(\omega)$ in a moving time window of a fixed length of L samples rather than over the entire available time interval, we obtain a two-parameter dependence $\lambda_1(\tau, \omega)$, where τ is the time coordinate of the window, for example, the moment of time corresponding to the right end of the window. The dependence $\lambda_1(\tau, \omega)$ may be represented by lines of level or volume surfaces, and the bursts of λ_1 correspond to the time intervals τ and frequency bands in which the synchronous behavior of the scalar components of the initial multidimensional time series is the most pronounced.

A specific feature of geophysical monitoring systems is the physical inhomogeneity of the time series obtained at different sites or at the same site of measurement. An example of this is hydrological data from the network of the Petropavlovsk research site. In spite of the heterogeneity and different scale of these data, their common features are that all of the data are measured simultaneously and, to some extent, reflect the processes occurring in the crust. Therefore, the question of detecting the collective behavior of the measured geophysical and geochemical fields with indication of the frequency bands and time intervals where such behavior is observed is of interest for different problems of monitoring. However, in this case, it is necessary to remove the different-scale effect of the scalar components of the initial vector time series. Furthermore, the spectral matrix $S(\omega)$ is estimated in a moving time window, i.e., for intervals of a relatively short length. Therefore, to eliminate the predominance of low frequencies, before estimating $S(\omega)$, it is reasonable to turn to the series in increments and then remove the different scales, to normalize each of the scalar components to the unit sample variance [1]. These preliminary operations accomplish the normalization of the spectral matrix in each time window and allow us to process physically inhomogeneous information.

An increase in $\lambda_1(\tau, \omega)$, i.e., synchronization of variations in the different scalar components of the vector series, may be caused by the following factors: (f1) the presence of an external source with a large spatial correlation radius acting on all of the recorded parameters (usually the effect of meteorological factors); (f2) the presence of a unidirectional geodynamic process in the crust, in particular, consolidation of its matter in a region covered by the network; (f3) postseismic variations in geophysical and geochemical fields after a sufficiently strong earthquake.

Factor (f1) may be eliminated by the multidimensional compensation of the measurable external disturbances.

Synchronization of observations at different points of the survey grid at the expense of consolidation of small crustal blocks and an increase in the cohesion forces between their boundaries (factor (f2)) is geophysically a very interesting signal, because the signal reflects the inner dynamics of geostructures [1]. We rely upon the hypothesis that consolidation of the crustal matter in seismic zones may be considered, in some cases, as an earthquake precursor, since for energy to be accumulated, without being expended for small events, the earthquake preparation zone must be, to some extent, unified [9, 10]. Picking out signal (f2) with determination of the frequency ranges in which significant bursts of the statistics of $\lambda_1(\tau, \omega)$ are observed (i.e., determination of the characteristic frequency of a medium at the site of observations) and comparing the time intervals of the appearance of the bursts are an important part of low-frequency monitoring in seismic regions, because their realization may lead to the discovery of new earthquake precursors.

One more source of the synchronization of observations at different points of the network in seismic regions is postseismic variations in geophysical and geochemical fields after earthquakes (signal (f3)). Note that, when observed data possess the low sensitivity expressed in the prolonged plateau of a constant measured value (unfortunately, this takes place for many of the data processed here), signal (f3) after a strong earthquake may be only a synchronizing signal; i.e., a high sensitivity is required to detect signal (f1) and particularly (f2). Nevertheless, signal (f3) may also contain information on the preparation of strong earthquakes, since a regularity suggesting the preparation (for example, a regular increase or decrease in bursts of $\lambda_1(\tau, \omega)$ from event to event) may be traced in the intensity of responses to small and moderate earthquakes.

Let us dwell on the method used by Lyubushin [2]. Let $\mathbf{X}(t) = (X_1(t), \ldots, X_m(t))^T$, $t = 1, \ldots, L$, be a sample from an initial multidimensional time series in a window (for exactness, the first window) of the length of L samples, m be the dimension of the column vector $\mathbf{X}(t)$, and t be the discrete time (numbering the sequential samples); the superscript T indicates transposition. For brevity, we sometimes omit the argument τ, which is the time coordinate of a particular window.

Forming the series in the increment

$$\mathbf{x}(t) = \mathbf{X}(t+1) - \mathbf{X}(t), \quad t = 1, \ldots, L-1, \tag{1}$$

for each component $x_i(t)$, $i = 1, \ldots, m$, we find the sample estimates of the mean s_i and variance σ_i in the current window

$$s_i = \sum_{t=1}^{L-1} x_i(t)/(L-1),$$
$$\sigma_i^2 = \sum_{t=1}^{L-1} (x_i(t) - s_i)^2/(L-2) \tag{2}$$

and normalize each of the components to the unit variance

$$x_i(t) := (x_i(t) - s_i)/s_i, \quad i = 1, \ldots, m. \tag{3}$$

Then it is required to construct an estimate of the spectral matrix $S(\omega)$. Experience shows that, for small L, the nonparametric estimate used by Lyubushin [1] (through the Fourier transformation of samples in each window and frequency averaging of multidimensional periodograms) does not possess sufficient resolution in the frequency. Therefore, the parametric estimate with the use of the multidimensional autoregression is preferable [2, 8]:

$$\mathbf{x}(t) + \sum_{k=1}^{p} A_k \mathbf{x}(t-k) = \mathbf{y}(t), \tag{4}$$

where $p \geq 1$ is the autoregression order, A_k for $k = 1, \ldots, p$ is the mxm matrix of the autoregression coefficients, and $\mathbf{y}(t)$ is the m-dimensional series of identification residues, which is assumed to be a sequence of the independent Gaussian vectors with a mean of zero and the covariance matrix P.

To determine the matrices P and A_k, $k = 1, \ldots, p$, the multidimensional Durbin–Levinson procedure was used, for which it was necessary to calculate the sample estimates of the covariance mxm matrices beforehand:

$$R(k) = \langle \mathbf{x}(t+k)\mathbf{x}^H(t) \rangle, \quad k = 0, 1, \ldots, p,$$

where $\langle \ldots \rangle$ is the symbol of averaging over time, and superscript H indicates the Hermitian conjugation [8].

After determination of the matrices $\mathbf{P}$ and A_k, $k = 1, \ldots, p$, the complex matrix $S(\omega)$ is estimated by the formula

$$S(\omega) = F^{-1}(\omega)\mathbf{P}F^{-H}(\omega), \tag{5}$$

where the complex matrices $F(\omega)$ are

$$F(\omega) = \mathbf{I} + \sum_{k=1}^{p} A_k \exp(-i\omega k), \tag{6}$$

i is the imaginary unit, $\mathbf{I}$ is the unit (mxm) matrix, and ω is the frequency.

Because of the matrix $S(\omega)$ being Hermitian and of the nonnegative exactness, its eigenvalues are real and nonnegative. Introducing notation for the eigenvalues of the matrix $S(\omega)$ and arranging them in decreasing order, we have

$$0 \leq \lambda_m(\omega) \leq \ldots \leq \lambda_2(\omega) \leq \lambda_1(\omega); \tag{7}$$

i.e., λ_1 and λ_m are the maximum and minimum eigenvalues, respectively.

The object of further analysis in the offered approach [1, 2] is the frequency functions $\lambda_i(\omega)$ calculated in the sequential time windows of the length of L samples taken with the mutual shift of ΔL samples ($1 \leq \Delta L \leq L$).

CHARACTERISTICS OF THE NETWORK AND INPUT DATA

At the Petropavlovsk geodynamic research site, Kamchatka, Institute of Volcanology, Far East Division, Russian Academy of Sciences, monitoring is carried out at hydrogeological holes and thermal springs with the goal of searching for strong earthquake precursors. The hydrogeological stations are located in the central part of the eastern coast of Kamchatka in the suburbs of Petropavlovsk–Kamchatski and Elizovo (Fig. 1).

The Pinachevo station includes the self-discharging 1261-m deep gassing hole GK1 and three captured weakly thermal springs. Hole GK1 discharges the subartesian thermal waters that are distributed in Cretaceous, Neogene, and Quaternary sedimentary–volcanic deposits. The Pinachevo station is located in the Petropavlovsk deep fault zone of the NW strike separating the areas of the eastern Kamchatka volcanic belt from the nonvolcanic areas of the Malko–Petropavlovsk transverse dislocation zone [12]. Changes in the regime of the Pinachevo water manifestations under the seismicity effect were described in detail elsewhere [13–19], and the geological characteristics of the geological and hydrogeological conditions of the areas of the stations were presented by Kopylova *et al.* [18].

The regime of nitrogen–methane thermal waters with a temperature from 5.5°C (spring 3) to 18°C (hole GK1) and mineralization from 0.2 g/l (spring 3) to 9 g/l (hole GK1) is examined at the Pinachevo station. The chemical composition of the observed water manifestations reflects the degree of mixing of the mineralized chloride Ca–Na waters ascending in the discharge zone (the chemical type of the water is determined by the component content above 25 equiv % in the sequence from a lesser value to a greater one) with fresh groundwaters. In particular, the least diluted water in hole GK1 has a chloride calcium–sodium composition, and the composition of the considerably more diluted

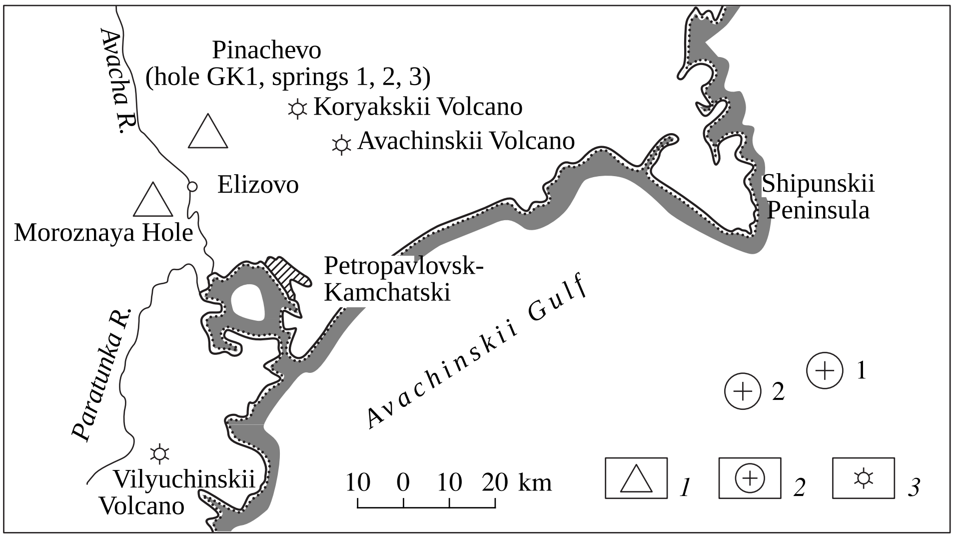

Fig. 1. Schematic location of sites of hydrogeological observations. (*1*) Hydrogeological station, (*2*) earthquake epicenters (1, October 6, 1987; 2, March 2, 1992), (*3*) volcanos.

waters of the springs varies from magnesium–sodium chloride–hydrocarbonate (spring 3) to sodium hydrocarbonate–chloride (spring 2). The composition of the free gas liberated from hole GK1 is dominated by CH_4 (approximately 80 vol %) and N_2 (approximately 20 vol %); Ar (0.12 vol %), CO_2 (0.23 vol %), and He (0.23 vol %) are also present. The remarkable feature of the regime of the Pinachevo water points is a weak manifestation of the seasonal variations in the spring debits and their almost complete absence in variations of the hole GK1 debit and the chemical composition of water and gas.

The Moroznaya station includes the self-discharging 600-m deep hole 1, raising the pressure crack–vein waters distributed in the Miocene tuffs. The discharge debit of the hole is 1.5 l/s, and the temperature of the water is 15–17°C. The welling-out water has a sulfate sodium–calcium composition with a mineralization of 0.2 g/l.

In the regime of the Moroznaya hole 1, seasonal variations in the debit and water temperature, as well as the relative stability of chemical composition of the water, are noted. Anomalous variations, which mainly occur in the hydrogeochemical parameters of the Moroznaya hole and are related to strong earthquakes, are presented elsewhere [16, 18, 19].

In 1986–1992, seismic activity in the area of the Petropavlovsk research site became stronger. According to data from the Petropavlovsk seismic station, more than 60 earthquakes occurred in the Petropavlovsk–Kamchatski area in this period and produced ground motions of the intensity from II to VI. Moreover, only seven of the earthquakes caused appreciable variations in the regime of the observed water manifestations (Table 1) [18]. In 1993, two VI-intensity earthquakes with magnitudes of 7.3 and 7.1 occurred in the south of eastern Kamchatka at a hypocentral distance of 120–230 km from the observation station.

Figure 2 shows some graphs of the input data for the period of 1986–1992. A period of nearly one year is noted for the water temperature in all of the water manifestations and debits of the Moroznaya hole 1 (Figs. 2b, 2c). Unidirectional trends are observed in the change of the indications of the hole GK1 regime (Fig. 2d). The postseismic variations are manifested in both the spring regime (Figs 2a, 2c, 2e, 2g) and gas composition of hole GK1 (Fig. 2h). Anomalous variations prior to the earthquakes of October 6, 1987, and March 2, 1992, manifested themselves in changes of the concentration of Cl^- in the water in hole GK1 (Fig. 2d) and the concentration of HCO_3^- in the water in Moroznaya hole 1 (Fig. 2f).

After the occurrence of the earthquakes listed in Table 1, the debit of spring 1 increased with a minimum amplitude of 0.1 l/s (Fig. 2a). As indicated earlier [13], the debit of spring 1 responded to seismic shocks most regularly as compared with the other indications. A change in the chemical composition of water in spring 1 was observed after six earthquakes (1–4, 6, and 7 in the table), and, furthermore, the concentration of Cl^- (Fig. 2e) and other components increased. Postseismic responses only to the three strongest earthquakes (2, 4, and 7) were observed in the regime of springs 2 and 3. The effects of earthquakes 2 and 7, whose epicenters are shown in Fig. 1, were manifested in the regime of holes GK1 and Moroznaya. Anomalous variations in some indications, for example, the concentration of Cl^- in the water in hole GK1 (Fig. 2e) and the concentration of HCO_3^- in the water in Moroznaya hole 1 (Fig. 2f), were fixed before these earthquakes occurred [18].

Main data on the 1986–1992 earthquakes resulting in a change in the regime of the monitored springs and holes at the Petropavlovsk research site

No.	Date	Distance from Pinachevo station, km	Magnitude	N latitude, deg	E longitude, deg	Depth, km
1	June 17, 1986	160	5.0	53.78	160.66	40
2	Oct. 6, 1987	130	6.6	52.85	160.24	34
3	Sept. 15, 1989	105	4.9	53.19	160.01	44
4	March 1, 1990	120	5.8	53.29	160.23	24
5	Dec. 19, 1990	155	6.1	52.77	160.65	24
6	April 8, 1991	170	4.7	52.36	158.21	139
7	March 2, 1992	115	7.1	52.82	159.99	40

Observations made over the course of many years in the springs and holes at the Petropavlovsk research site are conducted once every three days by the standard method. In visits to the stations, the debits are established by the volume method, the temperature of water in the outflow is measured by a standard thermometer with a scale factor of 0.2°C, and water and gas are sampled. A wide set of hydrogeochemical indications, including the concentrations of Cl^-, HCO_3^-, and H_4SiO_4, is determined. The argenthometric method with rhodanate is used to measure the Cl^- concentration, and the acidimetric method including recording the titration end point with a pH-meter is employed to determine the concentration of HCO_3^-. The error in the determined concentrations of Cl^- and HCO_3^- does not exceed 2%. The content of H_4SiO_4 is analyzed by the method of single-ray measurement with a Spekol photoelectric spectrometer; the measurement error is ±10%. The gas chronometer LKhM-8 is employed to measure CH_4, N_2, CO_2, and Ar in samples of free gas. The atmospheric pressure and temperature of air are also recorded at the station.

The main results of the observations at the Pinachevo and Moroznaya stations have been presented in previous papers [13–19] that discuss, mainly, the individual features of particular water manifestations and indications of the regime affected by both strong earthquakes and the seismic regime of the Kamchatka seismic zone as a whole.

RESULTS OF MULTIDIMENSIONAL DATA PROCESSING

Figures 3–9 present the dependences $\lambda_1(\tau, \omega)$ in the form of lines of level and volume surfaces for different combinations of the scalar time series for 1986–1992. The long vertical numbered bars along the time axis in graphs of level lines correspond to the moments of time of earthquakes. The spectral matrix was estimated in a moving time window of the length of 100 samples (300 days) taken at the mutual shift of 20 samples (60 days), with the use of the parametric model of third-order multidimensional autoregression. The points in the time axes correspond to the right ends of the moving time windows, and, for this reason, the moment of time of the first earthquake is not shown (it is located within the first window). The frequency band studied is determined by the sampling interval corresponding to three days (hence, the maximum frequency is 1/6 day^{-1}) and by the 300-day length of the time window (hence, the minimum frequency is 1/300 day^{-1}). The dependence $\lambda_1(\tau, \omega)$ is represented by level lines (left graph) enabling one to see the details of the volume surface (right graph) and helping to estimate quickly the scale of variations.

Let us turn to the dependence $\lambda_1(\tau, \omega)$ (Fig. 3) for the four-dimensional series of the concentration of Cl^- in the water in hole GK1 and sources 1, 2, and 3. We note the three significant maximums in the dependence $\lambda_1(\tau, \omega)$ at low frequencies. By comparison with the moments of time of the earthquakes, it is clear that the maximums are referred to a signal of the type (f3), i.e., the synchronization by postseismic motions after events 2, 4, and 7. Note that thickening of the level lines upon approaching the maximums begins a few days earlier than the events themselves (about two weeks prior to events 2 and 4 and about one month prior to event 7); i.e., a signal (f2) changing to (f3) is observed.

Figure 4, showing $\lambda_1(\tau, \omega)$ for the five-dimensional series of the HCO_3^- concentration in the water in the Moroznaya hole and the Pinachevo water manifestations, repeats, in many respects, Fig. 3, except for the absence of the middle bulge, which is a response to event 4. Note that the transition from the (f2) precursor synchronization to the (f1) postseismic one is also observed here.

According to some hydrogeological indications, including the concentrations of Cl^- and HCO_3^- [18], anomalous variations began 7 months to 27 days prior to the earthquake of October 6, 1987 (2), and 9 months to 12 days prior to the earthquake of March 2, 1992 (7). The multidimensional processing method [1, 2] allows

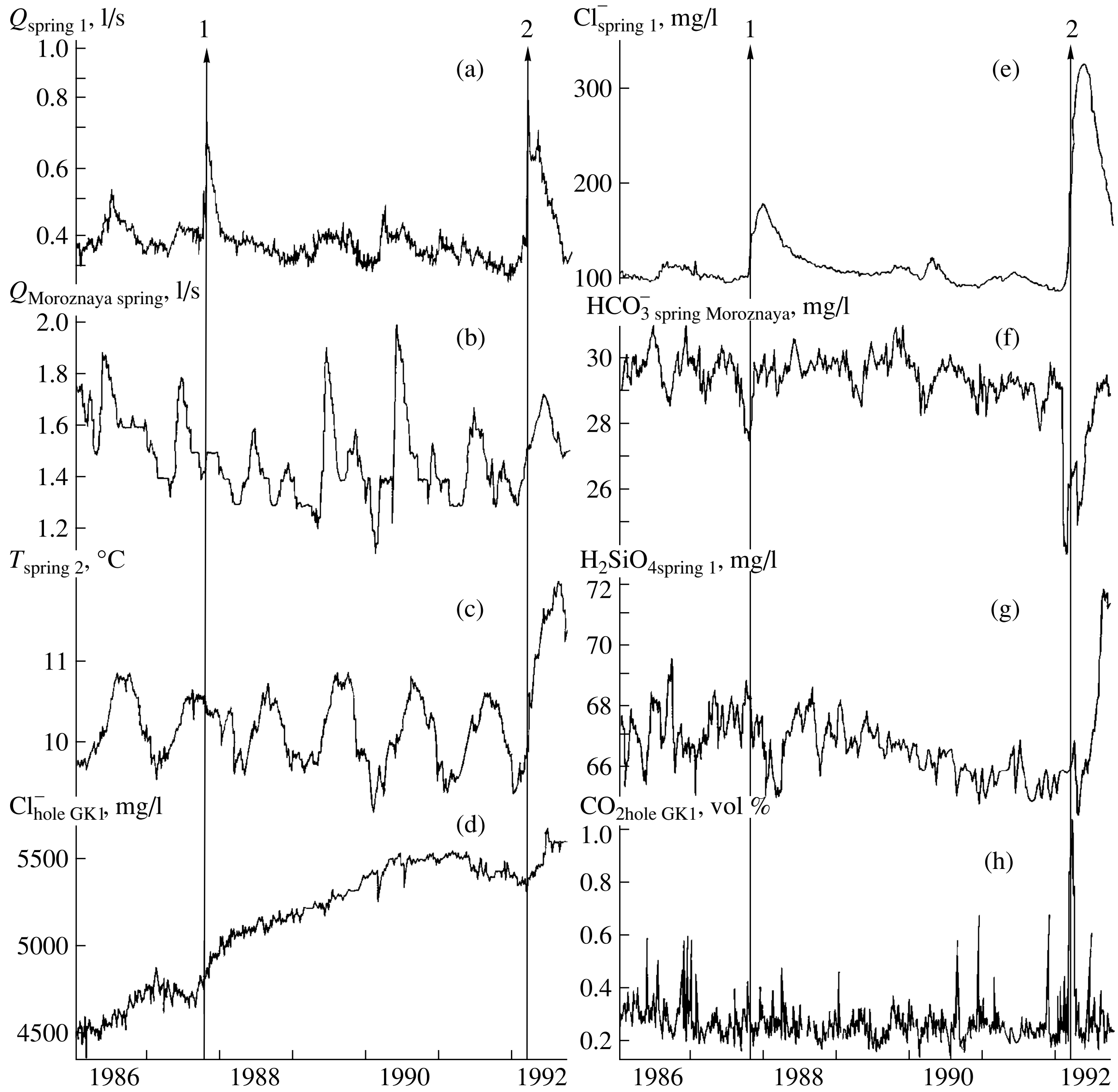

Fig. 2. Input data. (a) Debit of spring GK1; (b) debit of Moroznaya hole; (c) temperature of spring 2; (d) concentration of Cl^- in the water in hole GK1; (e) concentration of Cl^- in the water in spring 1; (f) concentration of HCO_3^- in the water in Moroznaya hole 1; (g) concentration of H_4SiO_4 in the water in spring 1; (h) concentration of CO_2 in the free gas in hole GK1. Vertical arrows are earthquakes: (1) October 6, 1987; (2) March 2, 1992.

us to identify a substantially new type of hydrogeological precursor, namely, the medium-term (from a few weeks to one month) increase in synchronization of the combined variation in the concentrations of Cl^- and HCO_3^- in a few holes and springs before the two strongest earthquakes for the last 20 years in the research area, which produced the V–VI ground motions in Petropavlovsk–Kamchatski.

The dependence $\lambda_1(\tau, \omega)$ for the four-dimensional series of the concentration of H_4SiO_4 (Fig. 5) has two significant maximums of the (f3) type: the first of them (α) is after event 4, and the second (β) is after event 7. The prevailing periods are about three weeks and one month for the first and second maximums, respectively. Note that a postseismic synchronization of variations in the concentration of H_4SiO_4 after earthquake 2 is absent (see table). In this case, it may be assumed that there are essential differences between the geodynamic environments and states of the medium in the preparation process and occurrence of earthquake 2, on one hand, and earthquakes 4 and 7, on the other.

In Figs. 6 and 7, a synchronizing signal is detected at low frequencies in the period from the second half of 1989 to the first half of 1990. As compared with earthquakes (see table), the indicated maximums of the com-

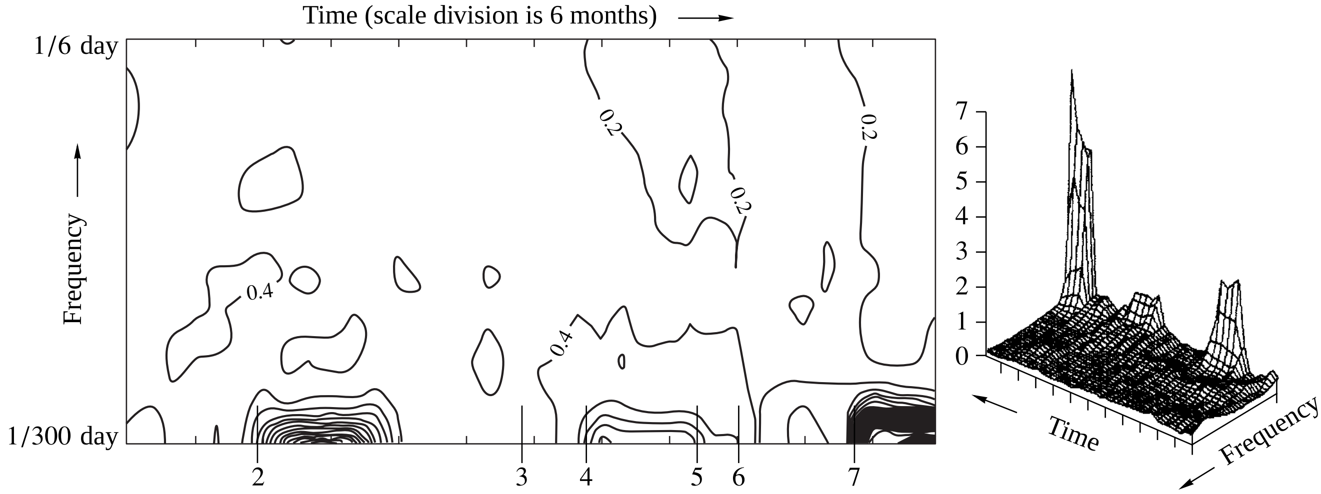

Fig. 3. Dependence $\lambda_1(\tau, \omega)$ for the four-dimensional series of the concentration of Cl^- in the Pinachevo water manifestations (hole GK1 and springs 1, 2, and 3).

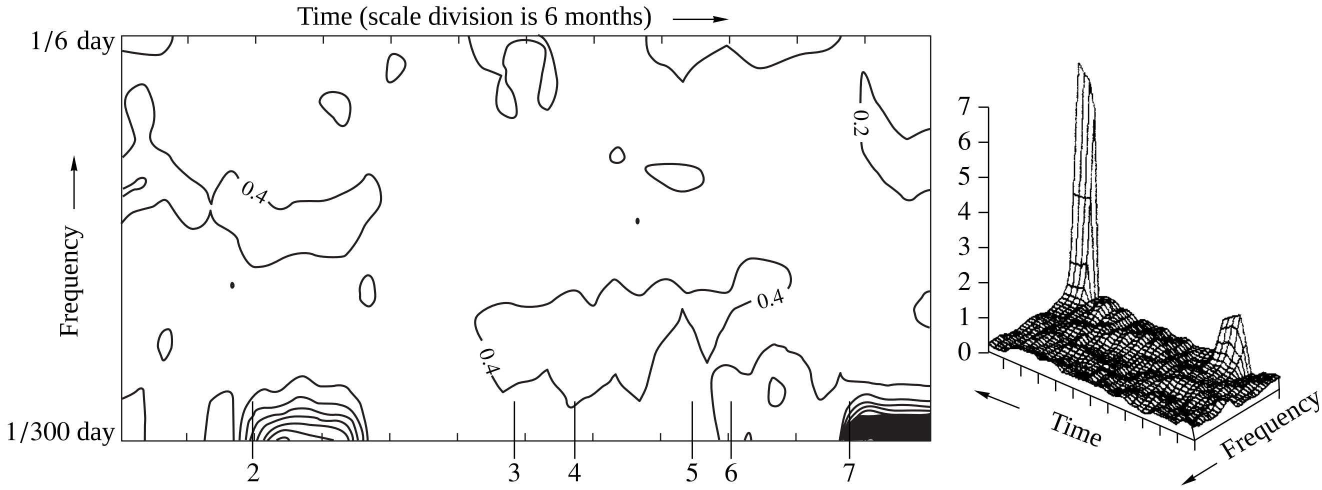

Fig. 4. Dependence $\lambda_1(\tau, \omega)$ for the five-dimensional series of the concentration of HCO_3^- in water in the Moroznaya hole and the Pinachevo water manifestations (hole GK1 and springs 1, 2, and 3).

mon behavior of the debits (Fig. 6) and the main indications of the Moroznaya hole regime (Fig. 7) may be considered the precursor synchronization (f3) before event 4, which, in both cases, is revealed almost one year before the earthquake.

Figure 8 generalizes the behavior of the main parameters of the hole GK1 regime and shows the most complicated dependence $\lambda_1(\tau, \omega)$. Four maximums (α, β, γ, and δ) can be observed moderately rising above the background and having prevailing periods of 300, 25, 14, and 7 days, respectively. It is of interest that the maximums shift with time toward higher frequencies; i.e., the synchronization is observed with time for more and more short-period variations. Whereas these maximums may be compared with the seismic regime, maximums α, β, and γ may be referred to as type (f2) (precursor synchronization): α is before event 2, β is likely before events 3 and 4, and γ is before event 7. As for burst δ, it is more likely of the (f3) type, i.e., the post-seismic synchronization after event 7. Note that anomalous variations in individual parameters of the hole GK1 regime (concentrations of Cl^- and free gases) were traced prior to the earthquake of October 6, 1987 (2), and particularly prior to the earthquake of March 2, 1992 (7) [18] (Figs. 2d–2h).

Figure 9 illustrates the chaotic behavior of the dependence $\lambda_1(\tau, \omega)$. This may be the consequence of both the crude determination of the temperature of the water and the fact that the time interval of sampling was too long (3 days).

Comparison of Figs. 5–8 shows that, in the period from 1989 to the first half of 1991, the maximums of

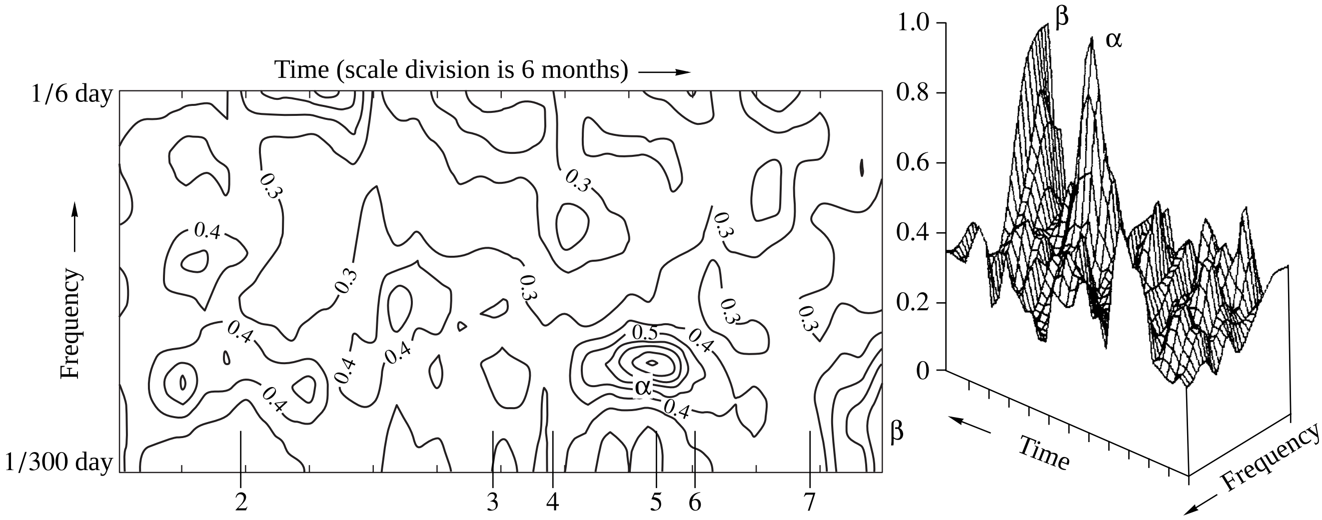

Fig. 5. Dependence $\lambda_1(\tau, \omega)$ for the four-dimensional series of the concentration of H_4SiO_4 in the water in the Moroznaya hole and water manifestations of the Pinachevo station (hole GK1 and springs 1 and 2).

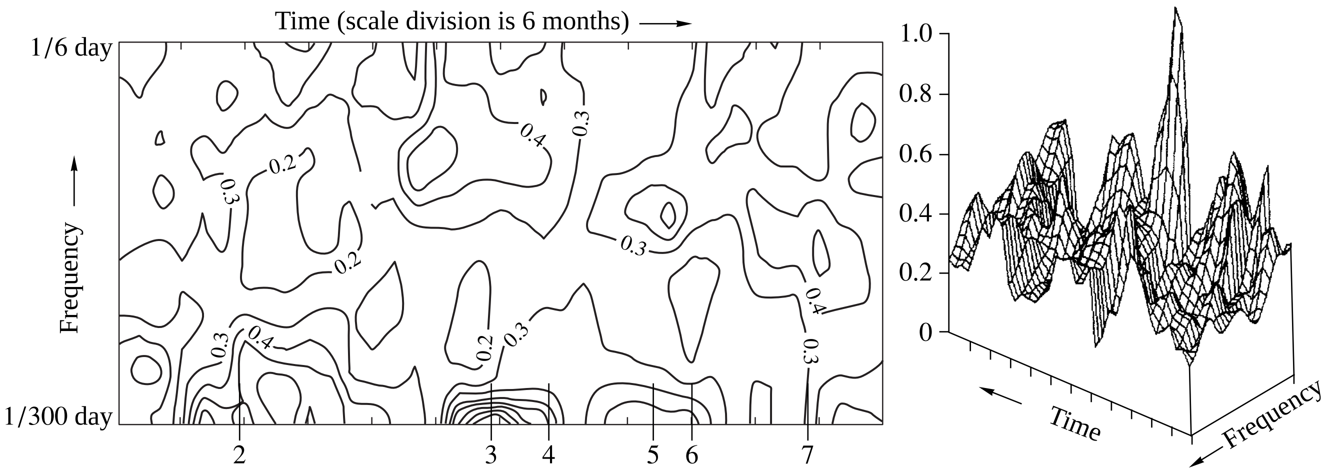

Fig. 6. Dependence $\lambda_1(\tau, \omega)$ for the four-dimensional series of debits in the Moroznaya hole and Pinachevo water manifestations (hole GK1 and springs 1 and 2).

$\lambda_1(\tau, \omega)$ in different holes (Moroznaya and GK1) are marked at the prevailing periods from 300 to 25 days by different indications (debit, chemical composition of the water, and the composition of free gas). This allows us to consider the time interval from 1989 to the first half of 1991 as a period of higher synchronization of the common behavior of the observed hydrogeological parameters and all of the regime water manifestations as a whole.

The described specific feature of the behavior of the observed set of hydrogeological parameters may be the manifestation of a unidirectional geodynamic process (factor (f2)) that may lead to the preparation and occurrence of strong earthquakes. Considering that seismic activity at the Petropavlovsk research site became stronger in the period of 1992–1993 (and three VI earthquakes with $M \geq 7$ occurred), the higher synchronization of the behavior of hydrogeological parameters in the spaced holes and springs may be viewed as a medium-term precursor of seismic activation in the form of earthquakes with $M \geq 7.0$.

Note that individual water manifestations have been recorded at the Pinachevo station since 1979 [17]. We do not give the results of their processing here because of the calm course of the dependence $\lambda_1(\tau, \omega)$ before 1986. Beginning from 1986, an enhancement of the trend toward synchronization, which is most clearly presented in Figs. 3–5, can be observed. Thus, the multidimensional processing of hydrogeological data obtained at the Petropavlovsk research site revealed two possible types of the synchronizing factor (f2): (1) the reflection of a regional geodynamic process

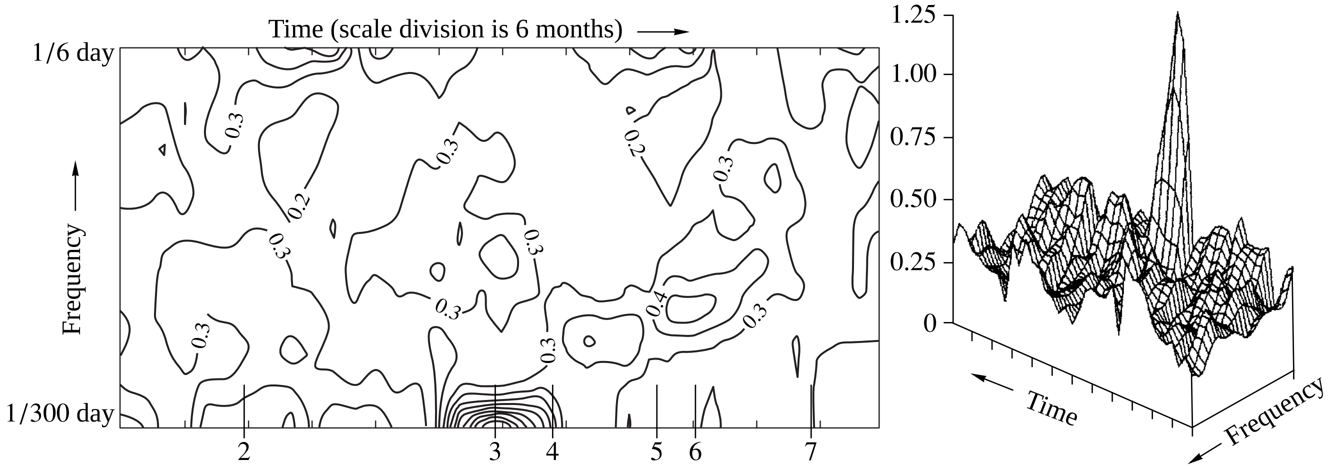

Fig. 7. Dependence $\lambda_1(\tau, \omega)$ for the four-dimensional series of temperature of water, debit, and the concentration of HCO_3^- and H_4SiO_4 in the water in the hole of the Moroznaya station.

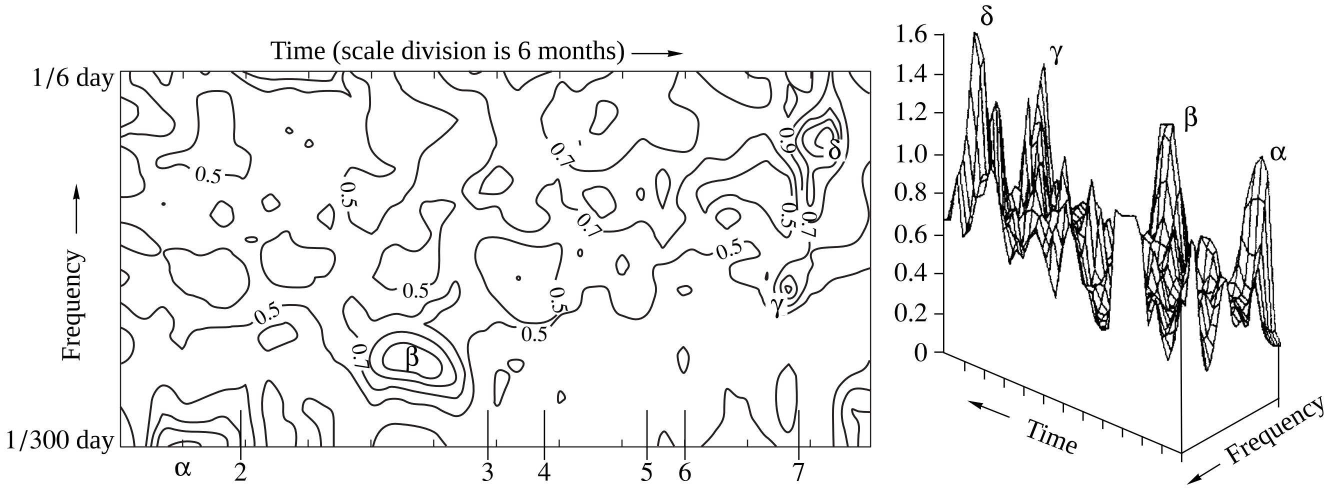

Fig. 8. Dependence $\lambda_1(\tau, \omega)$ for the ten-dimensional series of debit, temperature of water, concentrations of HCO_3^-, Cl^-, H_4SiO_4, and free gases Ar, CO_2, CH_4, He, and N_2 in hole GK1 at the Pinachevo station.

(increasing the synchronization trend in the variation of hydrogeological parameters) and (2) the reflection of the preparation process of the strongest earthquakes.

DISCUSSION

The multidimensional analysis of hydrogeodynamic and gas-hydrogeochemical data from the Petropavlovsk research site showed the outlook of the proposed method for mathematical formalization of the search for earthquake precursors. The fact that the method permits analysis of the entire frequency range determined by the sampling frequency and length of the time window is important.

Note that the resolution of the procedure based on estimating the cross-spectral characteristics of a series is sensitive to the accuracy of measurements and the large length of the sampling intervals. These are the shortcomings of the observation systems, in particular, at the Petropavlovsk research site. Due to these shortcomings, analysis in the high-frequency range, where hidden precursors may exist but remain beyond the reach of observation, becomes hopeless. In this respect, the Petropavlovsk research site must be equipped with sensitive transducers and automatic autonomous systems of recording of hydrophysical and gas-hydrochemical parameters, which can provide scanning at least once every hour.

The proposed method for the analysis of monitoring observations is still far from complete. In particular, it is not clear how the low-significance time series, which merely strengthen noise, can be removed. One method is the sequential elimination of one (with subsequent return) time series from the joint processing and estimation of the effect of the elimination (compared with the seismic regime). This method determines the

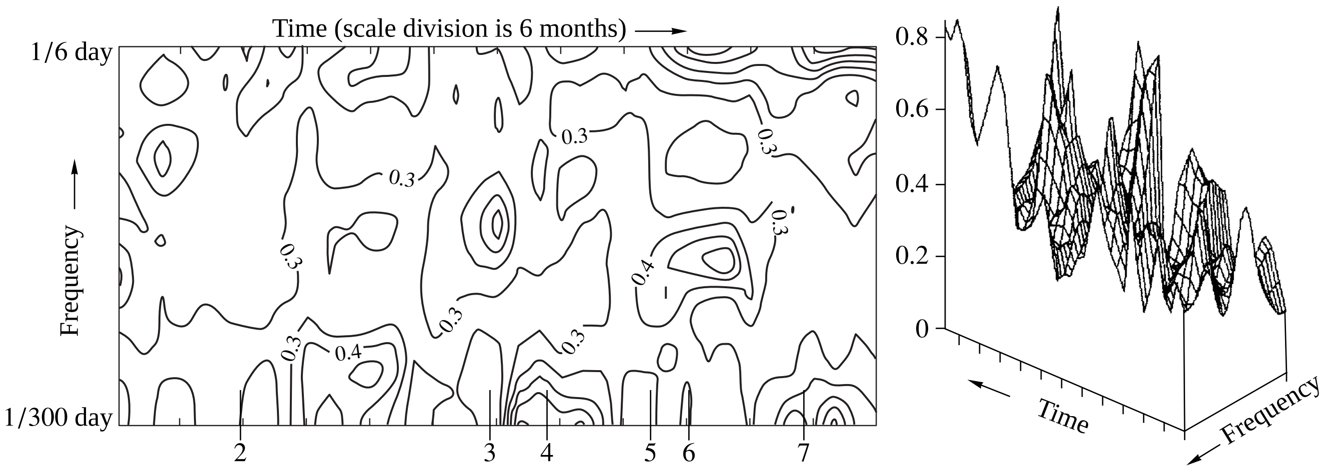

Fig. 9. Dependence $\lambda_1(\tau, \omega)$ for the four-dimensional series of temperature of the water in the Moroznaya hole at the Moroznaya station and Pinachevo water manifestations (hole GK1 and springs 1 and 2).

"worst" series. Then we can determine the next "worst" series among the remaining ones and so on, until only the "good" series remains. However, such a method is labor-consuming and not very applicable to the case of a large number of series. Furthermore, the formulation of the resolution rule (when an alarm must be announced) is unclear. Therefore, for the time being, the proposed method must be viewed as a way of representing the data, which is based on the general statistical ideas of reducing the dimension and identifying the most significant characteristics. Also, the method yields a program for the search of new precursors, the implementation of which requires a high-quality (with high sensitivity and sufficient sampling frequency) time series. Also, the resulting $\lambda_1(\tau, \omega)$ diagrams may be useful for the "expert" approach common in the practice of earthquake prediction, when different forms of data representation ("patterns" in Figs. 3–9) help to formulate a conclusion on a preparing earthquake by analogy with the precedents.

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