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Variation in the response function of the groundwater table with atmospheric pressure in the Southern Kuriles, Shikotan Island

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Introduction

This work continues the previous studies [*Lyubushin et al.,* 1992; *Lyubushin and Malugin,* 1993a, b; *Lyubushin and Latynina,* 1993; *Lyubushin,* 1993, 1994] devoted to the application of frequency-time analysis of the response functions and spectral matrices in multidimensional processing of time series of low-frequency geophysical monitoring. In particular, we consider time evolution of the response function of the groundwater level, measured in a well on Shikotan Island (Southern Kuriles), with variation in the atmospheric pressure.

Lyubushin et al. [1992] estimated the time variation of the amplitude-frequency function of transfer from pressure variations to linear strains of the crust measured in an aseismic region (Obninsk). They found a quasi-periodic evolutionary regime of the response in a frequency range from $1/16\ \mathrm{h}^{-1}$ to $1/6\ \mathrm{h}^{-1}$.

Lyubushin and Malugin [1993a, b] estimated the pressure-dependent response function for underground waters also in an aseismic zone at the Obninsk and Zelenyy settlements, Moscow province. In both cases, they found an appreciable decrease in the amplitude-frequency transfer function with increasing intensity of pressure variations at frequencies above $0.1\ \mathrm{h}^{-1}$, with the decrease in the response function reaching frequencies to $0.01\ \mathrm{h}^{-1}$. Note that such an effect was not observed in the evolution of the response of linear strains to pressure variations in Obninsk [*Lyubushin et al.,* 1992]. *Lyubushin and Malugin* [1993a, b] suggested that this effect was produced by weakening the action of high-frequency oscillations of the atmospheric pressure (at frequencies above $0.1\ \mathrm{h}^{-1}$) on the upper-crust strength. The decrease in the strength results from superimposing a mosaic spatial distribution of the high-frequency pressure variations on the block crustal structure in the vicinity of the measurement sites (the strength decreases owing to additional fluids expelled in fractures between the blocks at the expense of baric variations). The fact that a similar effect is absent in the case of linear strains is related to a specific effect of baric variations on the groundwater table: an increase in pressure, on the one hand, pushes a water column into the open well, and on the other hand, this increase squeezes out the water column by acting on the water-bearing bed through the crustal overburden. With decreasing strength of the overlying layer, the squeezing-out effect of atmospheric pressure begins to compete with the main, pushing-in effect, and this gives rise to a decrease in the amplitude response function.

Lyubushin et al. [1992] and *Lyubushin and Malugin* [1993a, b] considered the atmospheric pressure effect on crustal processes in an aseismic region. Of interest is to study this effect in such a highly seismic region as the Kuril Islands.

Initial Data

We considered data on measured groundwater level in the Shikotan Island from February 11, 1987, to December 31, 1991. This gives a time series length of 7140 readings at a discretization interval of $\Delta t = 6$ h. Figure 1 presents graphs of the initial data. Accuracy of the measured level is about 1.0 cm of water column, and that of the pressure is about 1.0 mbar. Thus the data are fairly crude, and their accuracy is nearly 2 orders lower than data used by *Lyubushin and Malugin* [1993a, b]. The well was drilled in a water bed at a depth of 300 m.

The experimental-methodical seismological party of the Institute of Sea Geology and Geophysics, Far East Division of the Russian Academy of Sciences, carried out measurements of the groundwater table, debit of flowing wells, sediments, and sea levels, and atmospheric

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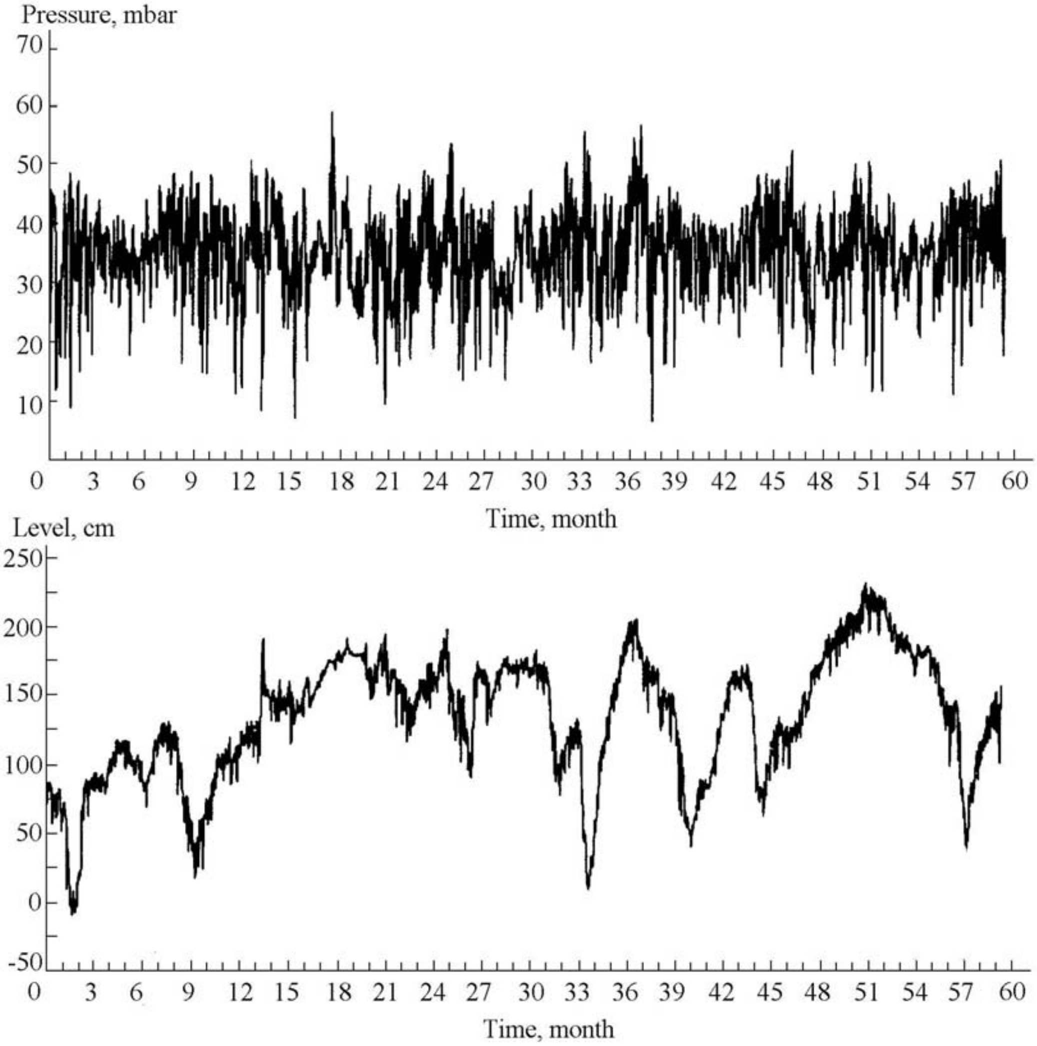

Figure 1. Initial time series of variations in the atmospheric pressure and groundwater level in a well on Shikotan Island from February 11, 1987, to December 31, 1991.

pressure in the Shikotan, Iturup, and Kunashir Islands from 1979 to 1992. Unfortunately, most of the time series obtained is fragmentary, i.e., it has considerable interruptions in the observed time intervals. Two time series plotted in Figure 1 are gratifying exception, since the series are continuous and cover a time interval of almost 5 years. It is natural that joint analysis of synchronous observations in the three islands, for example, by a principal component method in the frequency domain [*Lyubushin,* 1993, 1994] is of great interest (for determining time intervals and frequency bands in which synchronous indications of different parameters at these three sites are observed); also of interest is comparing the evolution of the response function at different sites. However, the quality of data does not permit such analysis, sending us in using only one point of measurements.

Since the discretization interval is $\Delta t = 6$ h, the minimum frequency (Nyquist frequency) is $1/12$ h^{-1}. Therefore we cannot extract time intervals of an increase in the intensity of baric variations at frequencies above 0.1 h^{-1}; i.e., the above effect of decrease in the amplitude transfer function with increasing the power spectrum of pressure [*Lyubushin and Malugin,* 1993a, b] cannot be verified. However, we can state that even if an effect similar to that found by *Lyubushin and Malugin* [1993a, b] existed, it was to large extent masked by an essentially stronger cause producing a quasi-periodic change in the amplitude of the response function at the frequencies considered below.

Processing Results

Problems of algorithms for estimating the response functions in a moving window were discussed in detail by *Lyubushin et al.* [1992] (see also the works by *Lyubu-*

shin and Malugin [1993a, b]). Therefore we only briefly consider the principal points.

To evaluate variation in the amplitude transfer function, we used a robast parametric method of estimation in moving overlapping time windows. Let us introduce notation: $U(t)$ is the temporal series of atmospheric pressure variations (input action), $Y(t)$ is the series of groundwater level variations (output signal), and t is dimensionless discrete time measured in units of the discretization interval. Initially, the series of increments are introduced:

$$y(t) = Y(t+1) - Y(t), \quad u(t) = U(t+1) - U(t) \quad (1)$$

Operation (1) is applied in the cases when low-frequency components dominate in the initial series; it is the case that takes place for the signals considered: power spectra of both the water level and atmospheric pressure strongly increase with decreasing frequency (following the power law).

Then the series $y(t)$ and $u(t)$ were passed through frequency filtration suppressing the components of the frequency bands:

$$[1/27, 1/23] \quad \text{and} \quad [1/13, 1/12]\ \mathrm{h}^{-1} \quad (2)$$

This operation is necessary for removing an intense narrow-band noise presented in the signal $y(t)$ and reflecting the tidal action, whose spectrum is mainly concentrated in the bands (2). Operation (2) is not quite correct, because it completely destroyed the information in the rejected frequency bands. However, this may be justified, first, since the bands are narrow, and second, since the parametric method used for the estimation of a small number of parameters is based on information from other frequency bands and interpolates the transfer function from the adjacent frequency bands to the bands (2). Tests of the narrow-band noise rejecting effect which were conducted with the use of artificial data with a given transfer function showed the estimates obtained are slightly different from the actual values (within the limits of statistical fluctuations).

Let L be the length in readings of a moving window, and τ be coordinate of the window end; i.e., the window contains data with reading numbers $\tau - L + 1 \leq t \leq \tau$. The estimate of the amplitude transfer function from u to y is denoted as $A(\tau, \nu)$, where ν is cyclic frequency. The length L of the reading time interval along with the discretization interval Δt give the frequency range to be studied:

$$\nu_{\min} < \nu < 1/2\Delta t, \quad \nu_{\min} \simeq 1/L\Delta t \quad (3)$$

The minimum frequency $\nu_{\min}$ is chosen on the condition that the corresponding harmonic fits in the reading interval L a sufficient number of times. Formal procedures for choosing the sufficiency condition are absent, and we set $\nu_{\min} = 5/(L\Delta t)$.

The purpose of this processing is to find dependence $A(\tau, \nu)$, where ν varies within the limits (3), and $1 \leq \tau \leq N - L + 1$, where N is the total number of readings in the analyzed series. Furthermore, values of τ were taken to be equal $\tau_k = 1 + (k-1)\Delta L$, $k = 1, 2, \ldots, [(N-L)/\Delta L] + 1$; i.e., the sequential time windows of length L were overlapped with $(L - \Delta L)$ readings.

Let us now turn to constructing the estimate in any window, for example, in the first window. We estimate parameters of models from an autoregressive class with the input action

$$y(t) + \sum_{k=1}^{n} a_k y(t-k) = \sum_{j=0}^{m} b_j u(t-j) + d + \varepsilon(t) \quad (4)$$

for L readings in the processing window: $y(t)$, $u(t)$, $t = 1, \ldots, L$. Here, $a_1, \ldots, a_n$ are autoregression parameters, $b_0, b_1, \ldots, b_m$ are regression parameters, d is the parameter of static shift, and $\varepsilon(t)$ is the residual of identification; it is assumed that the latter is a sequence of independent and equally distributed random values with zero mean. To estimate the parameters, the robast maximum likelihood method was used under the assumption that the residual ε has Gaussian distribution at small deviations and has Laplace distribution at great deviations [*Lyubushin et al.,* 1992]. In this case, the distribution function differs from the quadratic one, and its maximum is found by Newton's iterative method. The zero approximation was estimated by the least squares method [*Lyubushin et al.,* 1992]. Upon identifying the parameters of model (4), the amplitude transfer function was determined from

$$A(\tau, \nu) = \left| \left(\sum_{j=0}^{m} b_j z^j \right) \Big/ \left(1 + \sum_{k=1}^{n} a_k z^k \right) \right| \quad (5)$$
$$z = \exp(-2\pi\nu i)$$

where i is an imaginary unit.

To determine the autoregression and regression orders, n and m, we employed Akaike criterion [*Lyubushin et al.,* 1992], giving $n = 0$ and $m = 4$ for the used length L; i.e., we deal with the purely regression model of the fourth order.

Figure 2 shows the estimates obtained at the window length of $L = 500$ readings (3000 h $\simeq$ 4 months); the relative displacement of the windows is $\Delta L = 100$, which gives 67 intervals of estimation. Dependence $A(\tau, \nu)$ is present as level lines in Figure 2 and as three-dimensional surfaces in Figures 2b and 2c (a view from the side is taken in Figure 2b to emphasize that the minimums of $A(\tau, \nu)$ are observed for all frequencies ν at once).

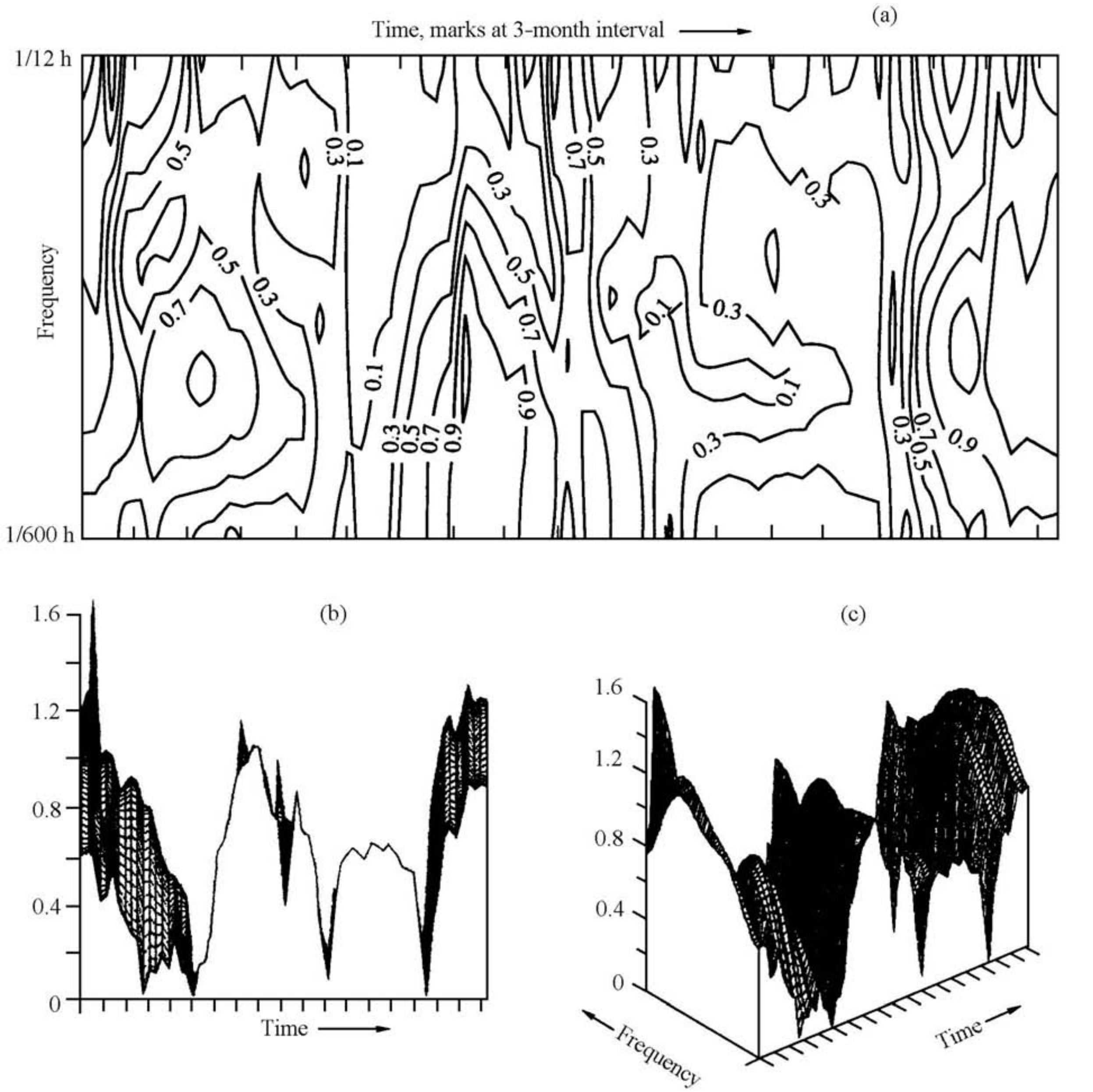

Figure 2. Evolution of the amplitude transfer function from baric variations to the groundwater level in the form of (a) isolines and (b, c) three-dimensional surfaces.

From Figure 1 it would be difficult to draw the conclusion on the frequency band in which the atmospheric pressure makes an essential contribution to variation in the groundwater table. It is only clear that unlike the level measurements in aseismic zones analyzed by *Lyubushin and Malugin* [1993a, b], baric variations have a small effect at low frequencies (otherwise, one would observe a visual correlation). Figure 3 illustrates the quadratic modulus of coherence spectrum γ^2 estimated from information on the entire available sample. The value of γ^2 shows which part of the power spectrum of groundwater level at a given frequency is, on average, attributed to baric variations for the entire time of observations. One can see that the period range in which the baric variations contribute above 20% lies between 90 and 450 hours. In the remaining frequency ranges, the relative contribution of tectonic signals (mostly at low frequencies) and noise components caused by low accuracy of measurements (at high frequencies) is essentially greater than the contribution of baric variations. This explains the difference of the estimated γ^2 from similar results of *Lyubushin and Malugin* [1993a, b], since the

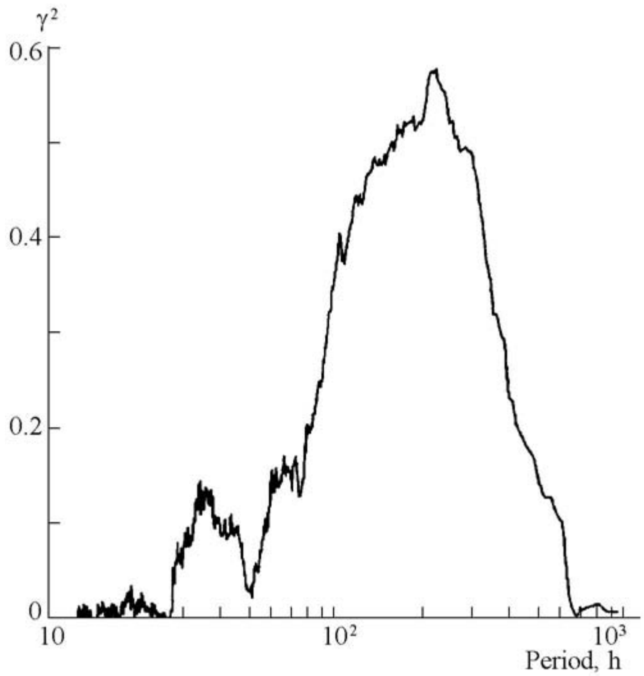

Figure 3. Estimation of the quadratic modulus of the coherence spectrum for baric variations and groundwater level.

intensity of low-frequency tectonic signals in aseismic regions is a priori weaker than that in the Kuriles. Furthermore, the accuracy of data interpreted by Lyubushin and Malugin is two orders higher than the accuracy of data above.

Interpretation

The main specific feature of the dependence $A(\tau,\nu)$ shown in Figure 2 is that the response function is quasi-periodic and has a period of about 1.5 years, which takes place at all frequencies in the interval $1/12\ \mathrm{h}^{-1} < \nu < 1/600\ \mathrm{h}^{-1}$. Since every estimate of $A(\tau,\nu)$ corresponds to an interval of nearly 4 months, the minimums in Figures 2a and 2b are referred to May to September of 1988, November of 1988 to March of 1989, and January to May of 1990. Note that these time intervals are not coincident with periods of intense rainfall, when one would expect weakening elastic properties of the outer crustal layer (in the weathering zone). This cause may be neglected for the considered occurrence depth of water bed. Furthermore, the minimum intervals do not correlate with weakening or strengthening seismic activity in the 500-km range.

A water bed is a gigantic volume strain meter acted upon by time-varying strain fields in the upper lithosphere. These strains are accumulated and averaged in the form of an internal formation pressure. Because of great sizes of the bed, variation in the formation pressure reflects large-scale strains, since small-scale strains being averaged in acting on the bed have mean close to zero. The groundwater level, measured in a well drilled to a water horizon, reflects both variation in the formation pressure and the effect produced by baric variation. The common approach is to compensate the baric effect (for example, with the help of method given by *Lyubushin and Latynina* [1993] and *Lyubushin* [1993]) and to consider the resulted residual including variations in the formation pressure caused by large-scale deformation and filtration of sediments. However, such an approach deals merely with an output signal of the well-bed system, whereas the use of the response function allows one to describe time variation of the internal state of the system by treating natural baric variations as a wide-band low-frequency sounding signal. Thus the dependence $A(\tau,\nu)$ reflects nonstationary conditions in elastic properties of the upper crust and in filtering properties of water bed.

We assume that the observed quasi-periodic nonstationary variations are related to change in lateral compressive lithospheric stresses produced by slow tectonic waves characteristic of Japan and Kuril Islands [*Kasahara,* 1985; *Bott and Deen,* 1973]. These waves occur from interaction of the elastic lithosphere with underlying viscous asthenosphere; their velocity in Japan is 20–40 km yr^{-1} [*Bott and Deen,* 1973]. In this case, an increase in the compressive stresses aids in increasing elastic rigidity of the crustal overburden and thereby gives rise to growth of the transfer function. To the contrary, a decrease in the stresses helps to decrease the response function in correspondence to the scheme suggested by *Lyubushin and Malugin* [1993a, b].

Conclusions

We evaluated the evolution of the amplitude-frequency transfer function from the variation of atmospheric pressure to change in groundwater level in a well on Shikotan Island in a period from February 11, 1987, to December 31, 1991. This evolution is quasi-stationary at frequencies from $1/12\ \mathrm{h}^{-1}$ to $1/600\ \mathrm{h}^{-1}$, and its characteristic period is about 1.5 years.

References

Bott, M. H., and D. S. Dean, Stress diffusion from plate boundaries, *Nature, 243,* 339–341, 1973.

Kasahara, K., *Earthquake Mechanics,* Cambridge University Press, New York, 1985.

Lyubushin, A. A., Jr., and L. A. Latynina, Compensation of meteorological noise in strain measurements, *Izv. Acad. Sci. Russ. Phys. Solid Earth, 3,* 98–102, 1993.

Lyubushin, A. A., Jr., Multidimensional analysis of temporal series of geophysical monitoring, *Izv. Acad. Sci. Russ. Phys. Solid Earth, 3,* 103–108, 1993.

Lyubushin, A. A., Jr., and V. A. Malugin, Statistical analysis of the groundwater table response to variation in the atmospheric pressure, *Izv. Acad. Sci. Russ. Phys. Solid Earth, 12,* 74–80, 1993a.

Lyubushin, A. A., Jr., and V. A. Malugin, Frequency-amplitude analysis of the groundwater table response to natural baric variations, in *Modeling Seismic Process and Earthquake Precursors, vol. 1,* pp. 56–63, Institute of Physics of the Earth, Moscow, 1993b.

Lyubushin, A. A., Jr., Classification of low-frequency states of systems of geophysical monitoring, *Izv. Acad. Sci. Russ. Phys. Solid Earth, 7–8,* 135–141, 1994.

Lyubushin, A. A., Jr., V. I. Osika, V. A. Pchelintsev, and L. S. Petukhova, Deformation response of the crust to variation in the atmospheric pressure, *Izv. Acad. Sci. Russ. Phys. Solid Earth, 2,* 81–89, 1992.

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