

Daily-Seasonal Variation in the Number of Remotely Observed, Pulsed, ULF Electromagnetic Earthquakes and the Spatial Distribution of Their Generation Zones on the Earth's Surface

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Abstract—Based on data from long-term observations at two geophysical observatories, Borok and College, distantly spaced in latitude and longitude, the results of remote observation of pulsed electromagnetic, ultralow-frequency (ULF) signals detected from distant earthquakes are analyzed *within minutes* of the seismic event. The daily and seasonal dependences of the frequency of occurrence of precursors in observatories and the nature of the spatial distribution of their generation zones on the Earth's surface are studied. Two maxima are distinguished in the daily distribution of the recurrence frequency: in the evening and morning hours of local time. In the seasonal course, there is a maximum in the spring and an increase in the winter months. In the spatial distribution, there is an uneven location of sources around the globe: they are grouped into separate zones and cells that reflect separate regions on the map with manifestations of seismo-electromagnetic activity. Examples are given to illustrate the appearance of precursors. It is noted that the dynamic spectra of signals from earthquakes occurring in different regions of the Earth's surface were similar. They were repeated at different magnitudes and focus depths and were observed in one time interval allocated relative to the moment of the earthquake. The results of the analysis indicated the universality of the processes of the generation of impulsive precursors preceding an earthquake, as well as the fundamental possibility of a short-term warning (of a few minutes) of an approaching earthquake.

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1. INTRODUCTION

This work is a continuation of the studies of pulsed, ultralow-frequency (ULF) electromagnetic signals that precede and accompany earthquakes that were carried out at the Borok geophysical observatory (Dovbnya et al., 2006; Dovbnya et al., 2008; Dovbnya, 2011; Dovbnya, 2014; Dovbnya et al., 2019).

Problems related to the search and recognition of earthquake precursors continues to be one of the main areas of geophysics. The experimental material accumulated to date indicates that it is promising to study such phenomena in the ULF range (0.001–10.000 Hz) (Ismaguilov et al., 2001). The first observations include those by Kopytenko et al. (1993), Molchanov (1990), and Molchanov et al. (1992), who reported fluctuations in the geomagnetic field before the devastating earthquake in Spitak. Also of note are works (Fraser-Smith et al., 1990; Bernardi et al., 1991) in which a powerful burst of ultra-low-frequency electromagnetic oscillations was detected and analyzed before the earthquake in Loma-Prieta. Interest in the study of precursors increased after earthquake in Kobe in 1995. In the works that followed the earthquake

(Hayakawa, 2009, 2013; hayakawa, Molchanov, 2002; Hayakawa, 2019), electromagnetic phenomena were considered in possible connection with earthquakes. Based on the results, the authors conclude that most of the observed precursors are electromagnetic. However, the situation with precursors remains ambiguous to date. Different manifestations of electromagnetic effects in disparate observations recorded for different times before the earthquake and the lack of repeatability of the results raise doubts about the reliability of the connection between the detected phenomena and earthquakes (Thomas et al., 2009a; Thomas et al., 2009b; Masci and Thomas, 2015). Some of the reports raise doubts and are disputed (Kosterin et al., 2015).

Against this background, attention is drawn to the question (with which the presented work is connected) about the possibility of the appearance before earthquakes of *impulsive* ULF electromagnetic signals that are capable of propagating over considerable distances along the Earth's surface. The possibility of the existence of an impulsive precursor was first pointed out by Moore (1964) back in 1964. He detected a short-term aperiodic increase by 100 nT in the level of the geomagnetic field 1 h and 6 min before the Big Earth-

quake ($M \approx 9.2$) in Alaska (United States) on March 27, 1964. The author explained the emergence of a pulsed ULF electromagnetic signal by the piezomagnetic effect of rocks subjected to compression. Similar effects in the pulsed electromagnetic field of the Earth prior to seismic events were reported in the literature (Varotsos et al., 1986; Malyshkov et al., 1987; Malyskov et al., 2009).

At the Borok geophysical observatory, which is located in the aseismic zone, an attempt was made to study the relationship between electromagnetic and seismotectonic processes based on data from continuous records of ULF variations of the Earth's electromagnetic field. As a result, it was possible to detect specific ULF electromagnetic pulses in the frequency band of 0–5 Hz that were observed in a selected and close temporal vicinity of earthquakes (0–5 min relative to the moment of the earthquake) but differed in the form of the dynamic spectrum from the known types of geomagnetic pulsations (Dovbnya et al., 2006).

In this work, we continue the study of ULF electromagnetic pulses that precede seismic events. The daily–seasonal variation of the probability of the appearance of signals is analyzed and the spatial distribution of their generation zones on the Earth's surface is considered based on remote observation data. Examples illustrating the appearance of precursors in various regions of the Earth's surface are given. The results are discussed.

2. MATERIAL AND METHODS

The ULF radiation was analyzed according to data from magnetic measurements at 2 midlatitude observatories: the Geophysical Observatory of the Borok Institute of Physics of the Earth of the Russian Academy of Science (58.1° N, 38.2°) for the period from 1973 to 1995 and at the high-latitude geophysical observatory College (64.9° , 148.0° E), which is located in the state of Alaska (United States) for the period 1973–1977. The starting materials for the analysis were records of ULF variations of the Earth's electromagnetic field. At the Borok and College observatories, an induction magnetometer was used for measurements with registration on an analog tape recorder. All observatories recorded two horizontal components of magnetic variations, north–south and east–west. The amplitude–frequency characteristic of the devices made it possible to analyze oscillations in the range (0.001–10.000 Hz). The analog records obtained at the Borok and College observatories were digitized and then subjected to spectral–temporal analysis with computer programs. Dynamic spectra of oscillations (spectrograms) were constructed. Information about the alternating electromagnetic field in the analyzed interval was reflected in the frequency–time coordinates. During the initial visual review, the known forms of signals of magnetospheric origin were

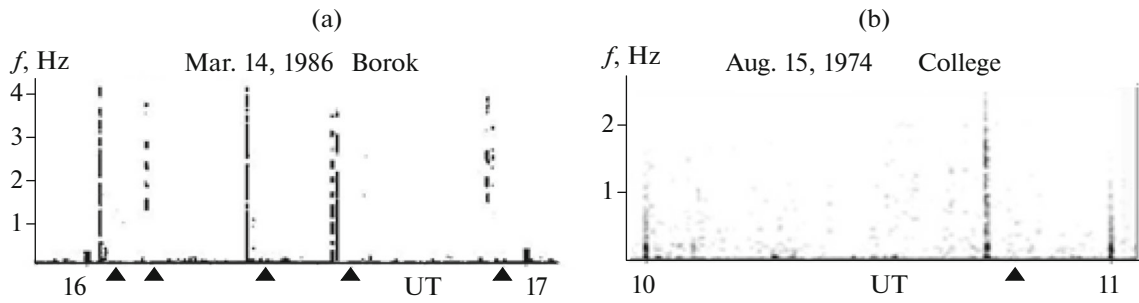
excluded from further analysis. Impulse signals, which differed from the known types of geomagnetic pulsations in the form of the dynamic spectrum, were included in the analysis and compared (with a binding statistical significance of $P = 0.86$) with the closest earthquake in the catalog (International Seismological Center, ISC Catalogues, (www.isc.ac.uk)) with specific geographic coordinates of the epicenter. The analysis methodology was detailed earlier (Dovbnya et al., 2006, 2019). Below, we will first give examples illustrating the appearance of precursors in various regions of the Earth's surface. We then examine the daily–seasonal behavior of observed impulse signals from distant earthquakes and consider the spatial distribution of their sources, i.e., the earthquakes during which the signals were observed, on the Earth's surface.

3. OBSERVATION RESULTS

During remote observation, signals from earthquakes occurring in different regions of the Earth's surface were recorded. They could be observed from both strong and weak earthquakes, while the threshold values of magnitude M were not marked for weak earthquakes. In total, about 300 h of magnetic recording were analyzed. During this period, there were over 5000 earthquakes with a magnitude of M from 3 and up. Signals observed in the first tens of seconds or minutes before the seismic event were recorded for approximately for 300 seismic events (earthquakes). Signals from remote earthquakes were observed in the form of either single or paired electromagnetic pulses in the frequency range of 0 to 5 Hz. Less frequently, series of three or more pulses were observed. As a rule, their dynamic spectra had a discrete structure. The signal amplitude did not exceed 20 pT, and the duration varied in the range of 20–50 s. At the Borok geophysical observatory, which is located in the aseismic zone, the precursors were recorded at a distance of up to 10000 km or more from the earthquake epicenter. With known coordinates, it was possible in each individual case to determine the distance from the epicenter to the observation station.

Figure 1 gives typical examples of the dynamic spectra of impulsive precursors observed at the Borok and College observatories. Here and below, dark triangles in the figures mark the moments of earthquakes. The figure captions give the following earthquake parameters: world time, geographic coordinates, depth h in km, and magnitude M .

Figure 1a shows cases of the appearance of electromagnetic pulses before earthquakes according to Borok observatory. As can be seen from the figure, the dynamic spectra of the signals observed with a statistical significance $P = 0.86$ from earthquakes occurring in different regions of the Earth's surface were similar. They were repeated at different magnitudes and focal depths and were observed in a selected time interval relative to the earthquake moment. Figure 1b gives an



Station	UT	φ	λ	h	M
Borok	1605:13	-5.286	154.379	233	5.2
Borok	1609:49	38.84	144.47	20	3.7
Borok	1625:45	24.780	122.873	23	4.3
Borok	1635:27	-41.136	174.642	31	3.4
Borok	1655:52	-30.1	-176.5	33	6.5
College	1046:10	28.85	139.2	408	5.3

Fig. 1. Examples of impulsive earthquake precursors based on observations at the Borok (a) and College (b) observatories.

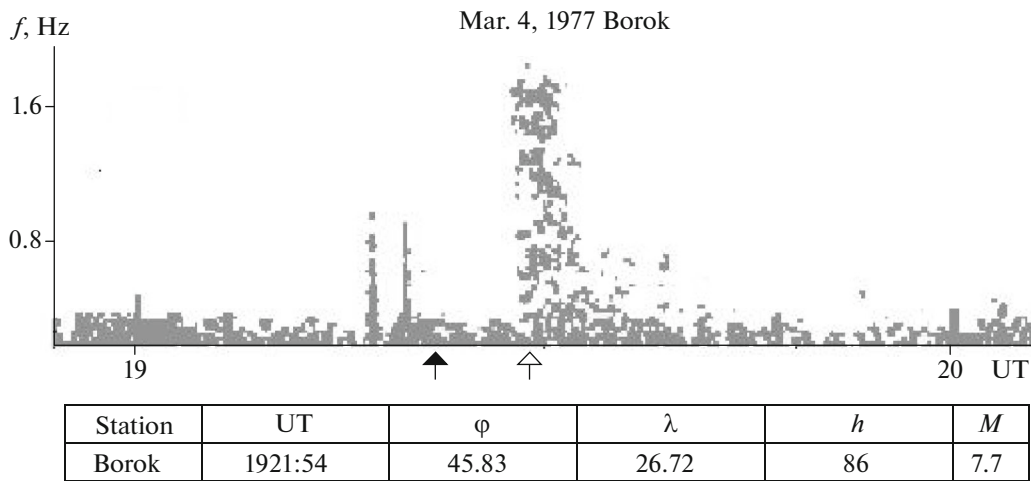


Fig. 2. An example of observing a seismic wave from an earthquake in Romania on March 4, 1977. A seismic wave (light arrow) was recorded at Borok 6 min after the moment of the main shock.

example of the registration of an impulse-precursor of an earthquake in Japan with $M = 5.3$ according to observations at the College observatory.

During strong earthquakes at Borok observatory, it was sometimes possible to observe the arrival of a seismic wave. One such example is shown in Fig. 2.

A devastating earthquake with a magnitude of $M = 7.7$ occurred in Romania at 1921 UT on March 4, 1977. Tremors caused by the arrival of a seismic wave from the source of the main shock were felt even in Mos-

cow. The seismic wave (light arrow) was recorded at Borok, which is located at a distance of about 2000 km from the epicenter, 6 min after the moment of the main shock. Four minutes before the earthquake, two electromagnetic pulses were recorded at the Borok observatory, which were 10 min ahead of the arrival of the seismic wave.

It is interesting to note a property of the manifestation of seismoelectromagnetic activity discovered during the analysis: the recurrence of impulsive precursors in earthquakes that occur after the main shock

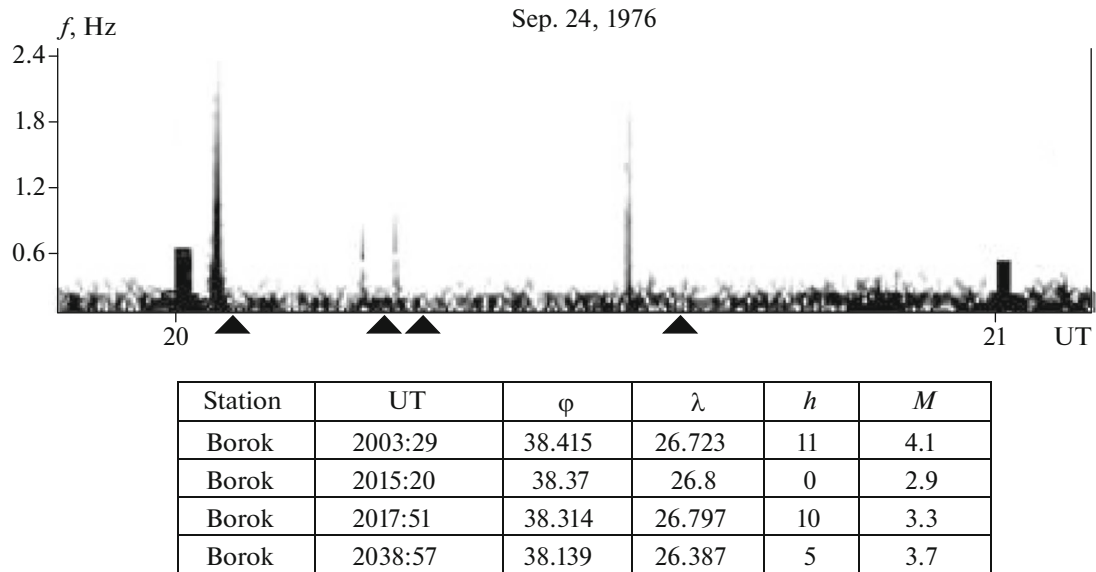


Fig. 3. Frequency of earthquake precursors following the main shock in the same region.

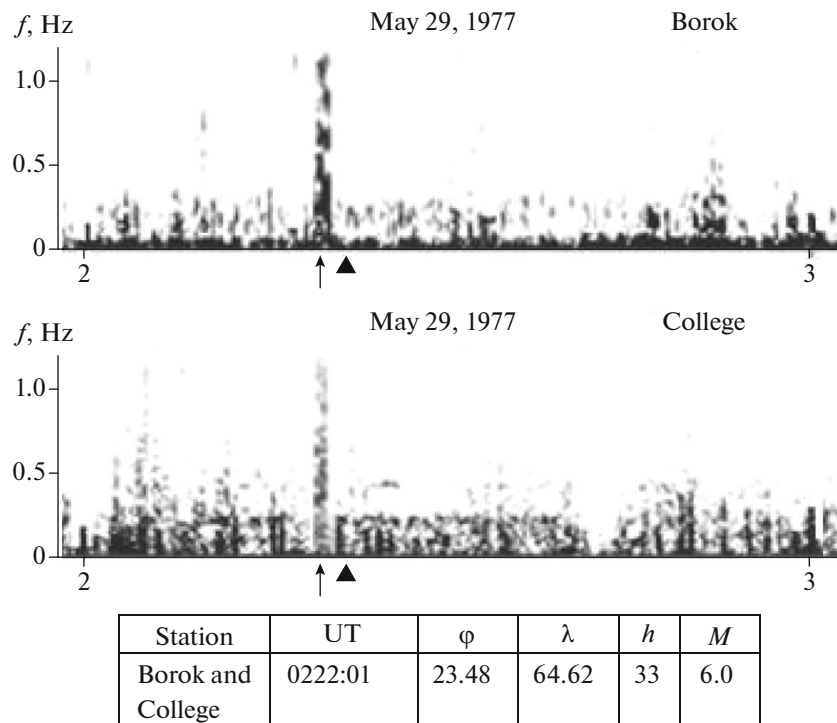


Fig. 4. Simultaneous observation of precursors at Borok and College observatories.

in the same region. Aftershocks pose a serious danger to the region affected by the first earthquake. The repetition of precursors can give a practical opportunity to give a prompt warning (in a few minutes) about the next earthquake. Figure 3 shows a fragment of the magnetic record at Borok of a series of earthquakes in Turkey, the epicenters of which were located quite close to each other (the frequency of occurrence was considered in detail by Dovbnya (2014)):

Let us pay attention to the dependence of the signal intensity on M .

Figure 4 gives examples of simultaneous observations of precursors in Borok and College (marked with arrows). It can be seen that, although the observatories are separated by almost 12 h in longitude and 10° in latitude, the precursors at both stations appear almost simultaneously and have a similar spectral shape.

3.1. Daily and Seasonal Dependences

During remote observation, signals are recorded at considerable distances from the earthquake epicenter (up to 10000 km or more). It is natural to expect that the probability of their observation at the observatory will depend on the conditions along the propagation path, which, in turn, are subject to daily and seasonal variations. Figure 5 gives the daily and seasonal dependences of the frequency of occurrence of precursors at Borok observatory.

Two maxima are distinguished in the daily distribution (Fig. 5a): the main one, which falls within the local morning hours ($LT = UT + 3$), and an additional one, which falls within the local evening hours. In the seasonal course (Fig. 5b), there is a maximum in the spring period, while the main increase in the number of events occurs in the winter months.

Figure 6 gives the same dependences for College observatory. The daily distribution also contains two maxima, but, unlike the maxima for Borok, the main one occurs in the afternoon hours ($LT = UT - 9$), and the additional one occurs in the evening. Two maxima are distinguished in the seasonal course for the probability of signal observation: the main one in the spring period and an additional one in the winter months.

3.2. Spatial Distribution of Generation Zones

During remote observation, signals coming from different places on the Earth's surface are recorded. This feature made it possible to analyze the geographical location of their generation zones. Figure 7 shows the distributions according to Borok observatory data (Fig. 7a, 228 events) and College (Fig. 7b, 78 events). The analysis shows a wide spatial, and, at the same time, uneven, arrangement of radiation sources. They are grouped into separate zones and cells that highlighting regions on the map with manifestations of seismoelectromagnetic activity. Observations at two observatories spaced apart in latitude and longitude indicate the same zones of ULF electromagnetic radiation with different statistics.

In the distribution of signal sources across the globe, there is a clear difference between the hemispheres. Most of them are in the Northern Hemisphere, where asymmetry is also noticeable in the latitudinal and longitudinal direction. Figures 8 and 9 show the distributions of ULF electromagnetic pulse generation zones over latitude (a) and longitudinal (b) for the Earth's belts for the Northern Hemisphere according to observations at the Borok and College observatories. The latitudinal belts were taken to be 15° wide, and the longitudinal ones were taken to be 30° wide. According to data from both observatories, a clear maximum in the latitudinal distribution is identified in the range $30^\circ - 45^\circ$; two maxima are noticeably manifested in the longitudinal direction in the

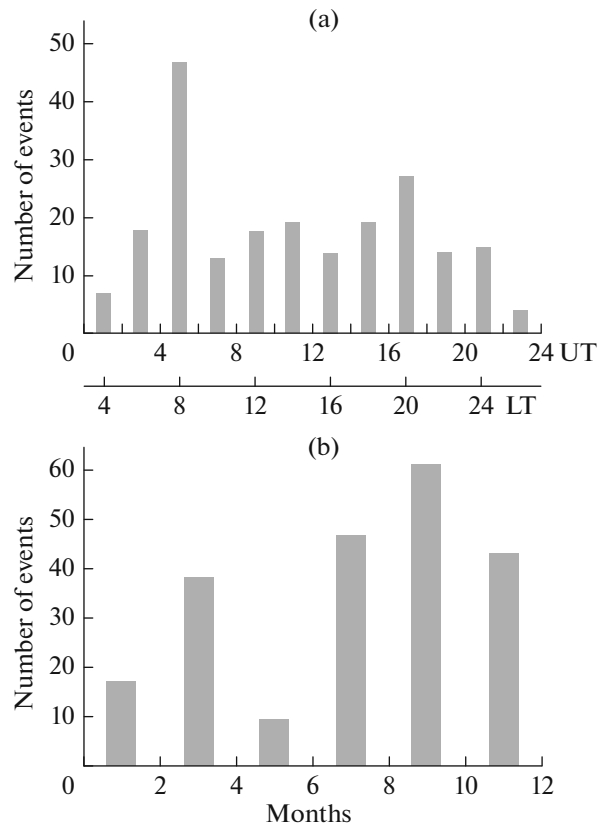


Fig. 5. Daily (a) and seasonal (b) distribution of the number of pulses at Borok observatory.

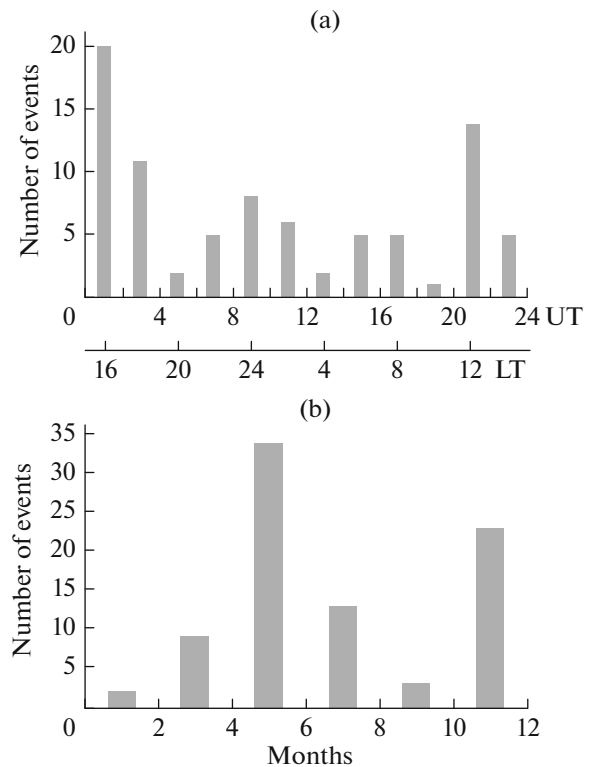


Fig. 6. Daily (a) and seasonal (b) distribution of the number of pulses at College observatory.

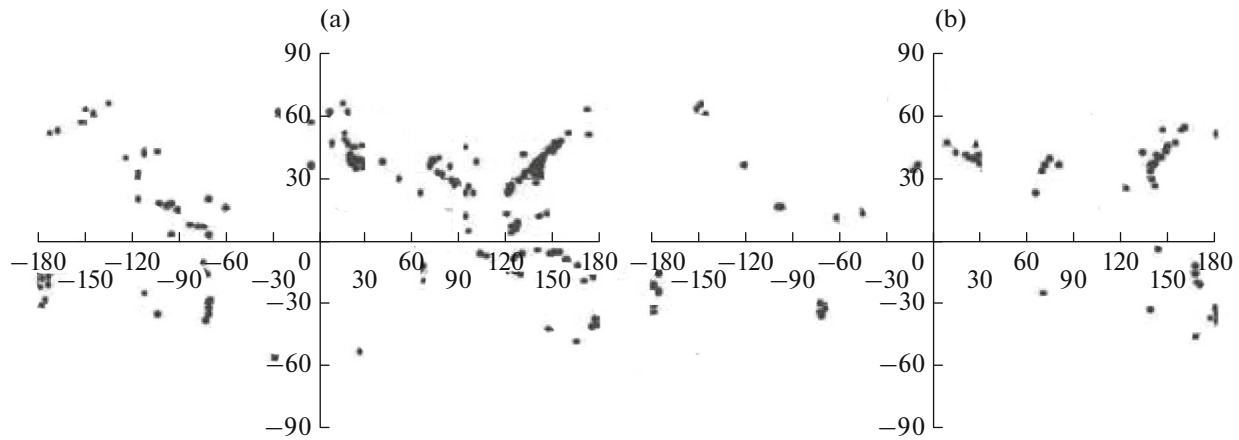


Fig. 7. Distribution of sources of ULF electromagnetic signals on the Earth's surface.

western sector: the main one in the range 120° – 150° and an additional one in the range 0° – 30° .

4. DISCUSSION AND CONCLUSIONS

Thus, according to data from long-term observations at two observatories separated in latitude and longitude, the daily and seasonal dependence of remotely observed, pulsed, ULF electromagnetic precursors was studied, and the nature of the spatial distribution of their generation zones on the Earth's surface was considered.

Let us try to give a qualitative explanation of the results.

1. The daily and seasonal dependence in the appearance of the number of pulses reflects the influence of local conditions and conditions along the signal propagation path. Different conditions along their path can lead to a different probability of the appearance of pulses with the same average seismic activity. An ionospheric waveguide can serve as a channel for signal propagation along the Earth's surface (Guglielmi and Troitskaya, 1973; Kosterin et al., 2015). Geomagnetic pulsations channeled in such a waveguide are capable of propagating along the Earth's surface at an Alfvén velocity of 500–1000 km/s over considerable distances.

The discreteness of the dynamic spectrum of pulses, which is characteristic of the ionospheric propagation of geomagnetic pulsations (Dovbnya et al., 2014), does not exclude such a possibility.

2. Analysis of the spatial distribution of sources of electromagnetic radiation, which are available via the remote recording of pulsed signals, showed their wide geographical distribution around the globe. The dynamic spectra of impulsive precursors were similar. They were repeated at different magnitudes and depths of the source and were observed in a selected time interval relative to the moment of the earthquake.

The detected signals can be considered a manifestation of the processes of the transformation of mechanical energy into the energy of electromagnetic radiation that precede the earthquake, which are not related to the processes in the source and do not depend on the parameters of the upcoming earth-

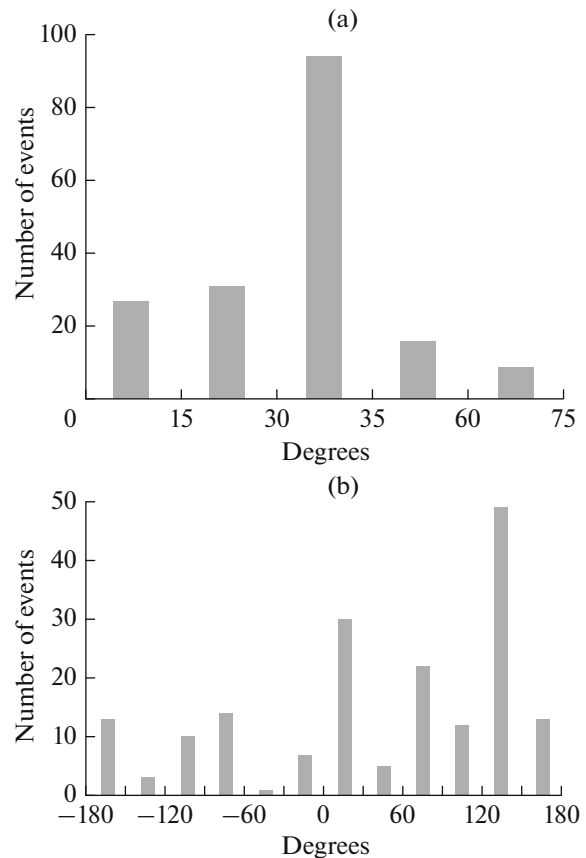


Fig. 8. Latitude distribution of ULF electromagnetic signal sources (a) and longitude (b) for the Northern Hemisphere from observations at Borok observatory.

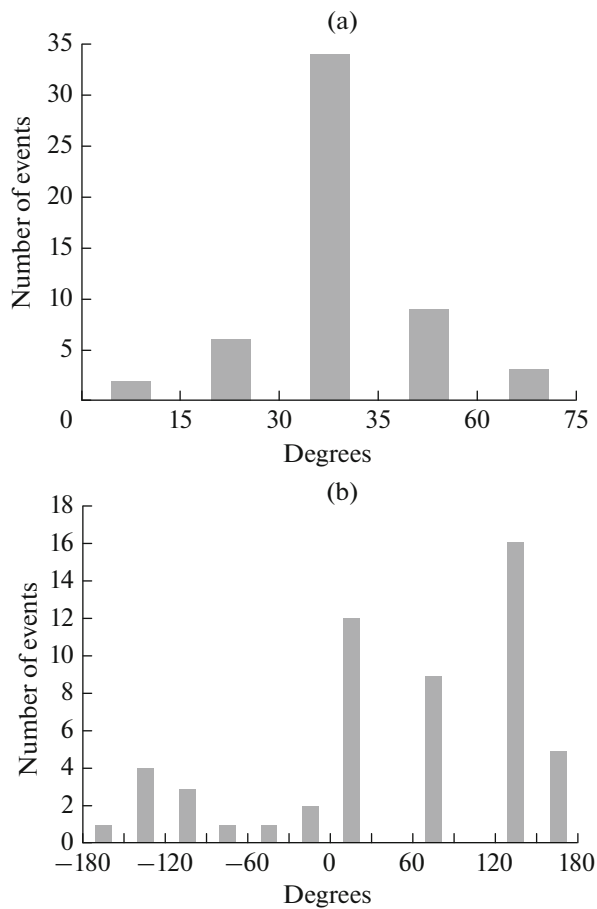


Fig. 9. Latitude distribution of ULF electromagnetic signal sources (a) and longitude (b) for the Northern Hemisphere from observations at the College observatory.

quake. The question of their possible physical nature was considered (Dovbnaya et al., 2019) within the framework of the Reid model (Reid, 1910), in which an earthquake is associated with the destruction of links at the boundary of two adjacent plates. It is assumed that a sharp compression of rocks prior to their destruction can lead to the generation of an electromagnetic pulse (piezomagnetic effect) or a series of two or more pulses with an inhomogeneous structure of interblock engagements. Within the framework of this hypothesis, one can find an explanation for the preferred appearance of precursors in a selected time interval that close to the moment of the earthquake and the absence of threshold values M .

The following conclusions are based on the results.

1. The appearance of electromagnetic signals before earthquakes is not a random act of an individual earthquake but is a manifestation of the processes preceding an earthquake that occur upon the transformation of mechanical energy into the energy of electromagnetic radiation. The similarity and repeatability of the spectral forms of impulsive precursors, regardless

of the region and earthquake parameters, allows us to make an assumption about the universality of the precursors of processes of earthquake signal generation.

2. The appearance of pulsed signals of a known spectral shape before earthquakes, their wide spatial distribution and interregional nature, and the similarity and repetition in aftershocks create the possibility of a prompt warning (within a few minutes) of an upcoming earthquake in most seismically hazardous regions of the Earth.

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REFERENCES

- Bernardi, A., Fraser-Smith, A.C., McGill, P.R., and Villard, O.G., Jr., ULF magnetic field measurements near the epicenter of the Ms 7.1 Loma Prieta earthquake, *Phys. Earth Planet Inter.*, 1991, vol. 68, pp. 45–63.
- Dovbnaya, B.V., On the effects of earthquakes in geomagnetic pulsations and their possible nature, *Geofiz. Zh.*, 2011, vol. 33, no. 1, pp. 72–79.
- Dovbnaya, B.V., Electromagnetic precursors of earthquakes and their recurrence, *Geofiz. Zh.*, 2014, vol. 36, no. 3, pp. 160–165.
<https://doi.org/10.24028/gzh.02033100.v36i3.2014.116069>
- Dovbnaya, B.V., Zotov, O.D., Mostryukov, A.Yu., and Shchepetnov, R.V., Electromagnetic signals close in time to earthquakes, *Izvestiya, Physics of the Solid Earth*, 2006, vol. 42, no. 8, pp. 684–689.
<https://doi.org/10.1134/S1069351306080052>
- Dovbnaya, B.V., Zotov, O.D., and Shchepetnov, R.V., Relationship of ULF electromagnetic waves with earthquakes and anthropogenic impacts, *Geofiz. Issled.*, 2008, vol. 9, pp. 3–23.
- Dovbnaya, B.V., Potapov, A.S., Guglielmi, A.V., and Rakhmatulin, R.A., On influence of MHD resonators upon geomagnetic pulsations, *Geofiz. Zh.*, 2014, vol. 36,

- no. 6, pp. 143–152.
<https://doi.org/10.24028/gzh.0203-3100.v36i6.2014.111053>
- Dovbnaya, B.V., Pashinin, A.Yu., and Rakhmatulin, R.A., Short-term electromagnetic precursors of earthquakes, *Geodyn. Tectonophys.*, 2019, vol. 10, no. 3, pp. 731–740.
<https://doi.org/10.5800/GT-2019-10-3-0438>
- Fraser-Smith, A.C., Bernardi, A., McGill, P.R., Ladd, M.E., Helliwell, R.A., and Villard, O.G., Jr., Low-frequency magnetic field measurements near the epicenter of the ms 7.1 Loma Prieta earthquake, *Geophys. Res. Lett.*, 1990, vol. 17, pp. 1465–1468.
- Guglielmi, A.V. and Troitskaya, V.A., *Geomagnitnye pul'satsii i diagnostika magnitosfery* (Geomagnetic Pulsations and Diagnostic of the Magnetosphere), Moscow: Nauka, 1973.
- Hayakawa, M., *Electromagnetic Phenomena Associated With Earthquakes*, Trivandrum, India: Transworld Research Network, 2009.
- Hayakawa, M., *Earthquake Prediction Studies: Seismo Electromagnetics*, Tokyo: Terra Scientific Publishing, 2013.
- Hayakawa, M., Seismo electromagnetics and earthquake prediction: History and new directions, *Int. J. Electron. Appl. Res.*, 2019, vol. 6, no. 1, pp. 1–23.
<https://doi.org/10.33665/IJEAR.2019.v06i01.001>
- Hayakawa, M. and Molchanov, O.A., *Seismo Electromagnetics: Lithosphere–Atmosphere–Ionosphere Coupling*, Tokyo: Terra Scientific Publishing, 2002.
- Ismaguilov, V.S., Kopytenko, Yu.A., Hattori, K., Voronov, P.M., Molchanov, O.A., and Hayakawa, M., ULF magnetic emissions connected with under sea bottom earthquakes, *Nat. Hazard Earth Syst.*, 2001, vol. 1, pp. 1–9.
- Kopytenko, Yu.A., Matiashvily, T.G., Voronov, P.M., Kopytenko, E.A., and Molchanov, O.A., Detection of ultra-low-frequency emissions connected with the Spitak earthquake and its aftershock activity, based on geomagnetic pulsations data at Dusheti and Vardzia observatories, *Phys. Earth Planet Inter.*, 1993, vol. 77, pp. 85–95.
- Kosterin, N.A., Pilipenko, V.A., and Dmitriev, E.M., On global ultralow frequency electromagnetic signals prior to earthquakes, *Geofiz. Issled.*, 2015, vol. 16, no. 1, pp. 24–34.
- Malyshkov, Yu.P. and Dzhumabaev, K.B., Earthquake prediction from parameters of the natural pulse electromagnetic field of the Earth, *Vulkanol. Seismol.*, 1987, no. 1, pp. 97–103.
- Malyshkov, Yu.P. and Malyshkov, S.Yu., Periodicity of geophysical fields and seismicity: Possible links with core motion, *Russ. Geol. Geophys.*, 2009, vol. 50, no. 2, pp. 115–130.
- Masci, F. and Thomas, J.N., Are there new findings in the search for ULF magnetic precursors to earthquakes?, *J. Geophys. Res.: Space*, 2015, vol. 120, no. 10, pp. 289–304.
<https://doi.org/10.1002/2015JA021336>
- Molchanov O.A. Discovering of ultra-low-frequency emissions connected with Spitak earthquake and its aftershock activity on data of geomagnetic pulsations observations at Dusheti and Vardzija, *Preprint of Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Russ. Acad. Sci.*, Moscow, 1990, no. 3 (88).
- Molchanov, O.A., Kopytenko, Yu.A., Voronov, P.M., Kopytenko, E.A., Matiashvili, T.G., Fraser-Smith, A.C., and Bernardy, A., Results of ULF magnetic field measurements near the epicenters of the Spitak (MS = 6.9) and the Loma-Prieta (MS = 7.1) earthquakes: Comparative analysis, *Geophys. Res. Lett.*, 1992, no. 19, pp. 1495–1498.
- Moore, G., Magnetic disturbances proceeding the 1964 Alaska earthquake, *Nature*, 1964, vol. 203, no. 4944, pp. 508–509.
- Reid, H.F., *The California earthquake of April 18, 1906 (Report of the State Earthquake Investigation Commission)*, vol. 2: *The Mechanics of the Earthquake*, Washington, DC: Carnegie Institution of Washington, 1910.
- Thomas, J.N., Love, J.J., and Johnston, M.J., On the reported magnetic precursor of the 1989 Loma Prieta earthquake, *Phys. Earth Planet. Inter.*, 2009a, vol. 173, no. 3, pp. 207–215.
<https://doi.org/10.1016/j.pepi.2008.11.014>
- Thomas, J.N., Love, J.J., Johnston, M.J., and Yumoto, K., On the reported magnetic precursor of the 1993 Guam earthquake, *Geophys. Res. Lett.*, 2009b, vol. 36, L16301.
<https://doi.org/10.1029/2009GL039020>
- Varotsos, P., Alexopoulos, K., Nomicos, K., and Lazaridou, M., Earthquake prediction and electric signals, *Nature*, 1986, vol. 322, no. 6075, p. 120.