

Analysis of the efficiency of earthquake prediction based on the anomalous behavior of ionospheric parameters on the eve of earthquakes in the Kamchatka region

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Abstract. A method is presented for short-term prediction of strong earthquakes, in which the precursors are considered the excess of current values of f_oF2 critical frequency of the ionospheric F2 layer over the median values in periods of perturbed state of the magnetosphere, the appearance of ionospheric disturbances: K-layer, Es-spread F-spread, the stratification of the F2 layer, Es is the r type. As predicted earthquakes were considered earthquakes with magnitudes $M \geq 5.0$. Assessment of the effectiveness of the forecast was carried out in the spring and autumn periods for 2013–2017 according to the methods of A. A. Gusev and G. M. Molchan. It is shown that the method under consideration has the best prognostic efficiency for seismic events with $M \geq 6.5$ magnitude.

1 Introduction

The study of solar-terrestrial relations revealed a direct relationship between solar activity and processes in the magnetosphere, ionosphere and lithosphere. However, there is a feedback that determines the influence of lithospheric processes of seismic regions on the ionosphere and magnetosphere. We can say that at the ionospheric and magnetospheric altitudes there is a kind of mapping and averaging of processes occurring in the earth's crust in areas of hundreds of kilometers. Any small impact on the ionosphere can lead to trigger effects with energy release significantly exceeding the energy of primary disturbance factors of solar or lithospheric origin. Modern research has established that the earth's crust affects the physical processes occurring in the upper geospheric shells. Therefore, in seismically active regions, any anomalous changes in the behavior of ionospheric parameters formed against the background of regular daily changes in the characteristics of the ionosphere due to the influence of the Sun can provide information about the processes of earthquake preparation [1–3]. In turn, each seismic region is characterized by its most informative features (anomalies) in the behavior of the ionospheric parameters, which can be identified with the precursors of earthquakes. In the Kamchatka region, such features as long-term studies of the ionospheric parameters dynamics on the eve of the earthquake, it can include the following [4–6]:

1. precipitation from several hours to several days before the earthquake of charged particles from radiation belts into the ionosphere (formation of a K-layer);

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2. formation of the diffusion sporadic layer Es (Es-spread) 1–3 days before the earthquake;
3. for 1–5 days on the background of the development of magnetic storms (in autumn and spring) abnormal increase in the critical frequency f_oF2 (increase in electron concentration), exceeding the median values (in the normal development of the magnetospheric storm in the ionosphere due to the vortex electric field there is a drift, which leads to the displacement of electrons to great heights and a decrease in their concentration).
4. formation of a diffusion layer F2 (F2-spread) lasting several hours in 1–3 days against the background of a quiet magnetosphere;
5. for 1–3 days stratification layer F2 in frequency and height (mode "H"), the so-called moving ionospheric disturbances.

2 Short-term earthquake prediction method based on anomalous behavior of ionospheric parameters

The paper uses the data of radiophysical observations performed by means of vertical radiosounding. Automatic ionospheric station (AIS) of vertical radioonde is located in Paratunka village ($\varphi = 52.97^\circ$ N, $\lambda = 158.25^\circ$ E). Observations are conducted once every 15 minutes in pulse mode at frequencies from 1 to 15 MHz. As an example, Fig. 1 shows ionogramms containing anomalies corresponding to features 4) (Fig. 1a) and 5) (Fig. 1b), listed in the previous section.

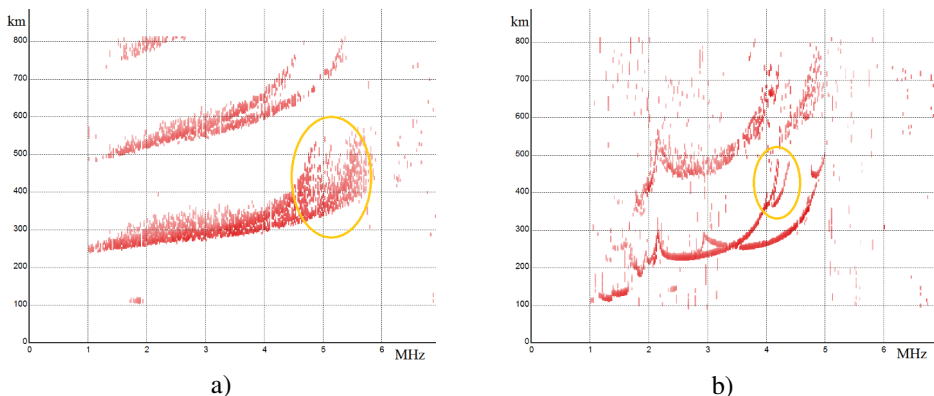


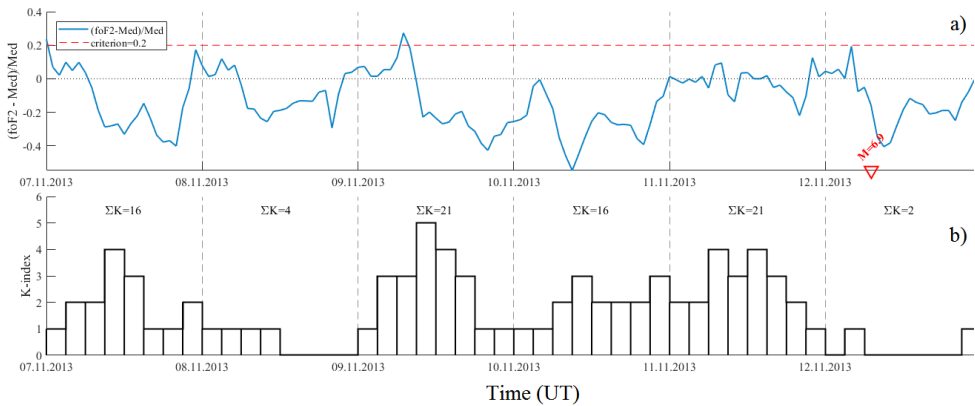
Figure 1. Examples of anomalous behavior of ionospheric parameters formed on the background of a quiet magnetosphere: a) diffusion layer F2 (F2-spread) lasting several hours (mode "F"); b) stratification of layer F2 in frequency and height (mode "H", moving ionospheric disturbances)

Table 1 shows the time (UT) of ionospheric disturbances, and Fig. 2 shows the deviation of the critical frequency f_oF2 from the median values and the change in the values of geomagnetic activity indices K before the earthquake that occurred on 12.11.2013 with the coordinates of the epicenter $\varphi = 54.64^\circ$ N, $\lambda = 162.44^\circ$ E, depth of hypocenter $h = 67$ km and magnitude $M = 6.9$.

The short-term earthquake prediction algorithm presented in this paper is based on a joint analysis in a sliding time window with a width $\Delta T = 5$ days with a step $\Delta t = 1$ day

Table 1. The duration of ionospheric disturbances during the period 09.11.2013–12.11.2013

ionospheric disturbances	09.11.2013	10.11.2013	11.11.2013	12.11.2013
K-layer	10:15-11:00		09:45-10:00 10:30-10:45	
Es-spread		06:15-06:30		
F-spread			09:15-09:30	11:15-14:00
The stratification of the F2 on frequency and height	22:30-22:45		02:15-02:30 08:15-08:30	01:15-01:30 03:30-03:45 04:30-04:45 07:15-07:30 08:00-08:15
Es type r	15:00-18:15	18:00-18:15	16:00-18:00	

**Figure 2.** Time series for the period 07.11.2013–12.11.2013: a) relative deviations of the critical frequency f_oF2 from its median values f_{med} ($\Delta f_oF2/f_{med}$) b) three-hour values of the K -index.

of the following ionospheric parameters: the critical frequency f_oF2 of the F2 layer, the manifestations of turbulence of the F2 and Es layers (F-spread and Es-spread), the F2 layer bundle in frequency and height (modes "H" and "V"), the formation of the corpuscular K-layer and the sporadic Es type r layer. The condition for declaring the beginning of the t_{alarm} alarm period was to perform the following criteria on the time interval ΔT for at least four considered ionospheric parameters:

- The excess of the critical frequency f_oF2 of the F2 layer of the median f_{med} values calculated over the previous 30 days, not less than 20% ($\Delta f_oF2/f_{med} \geq 0.2$) on the background of the development of a magnetic storm (total K -index values for the day $\Sigma K \geq 20$);
- Formation of the K-layer on the last day of the ΔT interval;
- The formation of the diffusion of sporadic Es layer (Es-spread);
- Formation of the diffusion layer F2 (F2-spread) during the last three days of the ΔT interval on the background of a quiet magnetosphere (three-hour values of the geomagnetic activity index during the day to $K \leq 2$);

- Stratification of the F2 layer in frequency and height during the last three days of the ΔT interval against the background of a quiet magnetosphere ($K \leq 2$);
- The formation of the sporadic Es layer of type r on the last day of the interval ΔT .

The duration of the alarm period is set to $t_{\text{alarm}} = 5$ days. The algorithm was tested on the time interval 01.01.2013–31.12.2017 in the spring and autumn seasons. As predicted seismic events were considered earthquakes of magnitude range $M \geq 5.0$, $M \geq 5.5$, $M \geq 6.0$, $M \geq 6.5$, which occurred at depths of 100 km in radius $r = 500$ km from the registration point of ionospheric observation IKIR FEB RAS in Kamchatka. The catalogue of earthquakes of the Kamchatka branch of the Federal Research Center "Unified Geophysical Service of RAS" [7] for 2013–2017 was used for the analysis.

3 Efficiency evaluation of the forecast method

Two approaches of A. A. Gusev [8] and G. M. Molchan [9] were used to assess the efficiency of the considered forecast method.

The reliability of the precursor R is defined as the ratio of the number of earthquakes $n(E_A)$ for which the precursor was allocated to the number of all earthquakes $n(E)$:

$$R = \frac{n(E_A)}{n(E)} \quad (1)$$

The validity of the precursor is defined as the ratio of the number of precursor anomalies $n(A_E)$ to the total number of isolated anomalies $n(A)$:

$$V = \frac{n(A_E)}{n(A)} \quad (2)$$

According to the results presented in Table 2, the reliability of the precursor under consider-

Table 2. . Dependence of the reliability and validity of the precursor on the lower threshold of the considered earthquake magnitudes M .

Magnitude M	$M \geq 5.0$	$M \geq 5.5$	$M \geq 6.0$	$M \geq 6.5$
$n(E_A)$	34	14	9	4
Missing earthquakes	66	28	8	2
$n(A_E)$	34	14	9	4
False anomalies	57	77	82	87
Reliability of the precursor R	0.34	0.33	0.53	0.67
Validity of the precursor V	0.37	0.15	0.1	0.04

ation is higher for earthquakes of higher magnitudes than for smaller ones. For earthquakes with magnitude $M \geq 6.5$, the reliability of R was 0.67. The validity of the precursor V takes the highest values for an earthquake with a magnitude $M \geq 5.0$ and is 0.34. Since the precursor can be assigned to several earthquakes (the group) and should be considered when deciding about the implementation of forecasting and estimating the time of trouble, it was applied the following approach: 1) forecast is the realized first earthquake forecast magnitude appropriate interval, 2) the alarm is removed, 3) next earthquakes, which would formally correspond to the same precursor anomalies are declared missing ("skip goal") [10].

The efficiency of the forecast by the A. A. Gusev's method is calculated for a specific spatial region and a certain energy range of earthquakes by the formula:

$$J_G = \frac{N_+/T_{\text{alarm}}}{N/T} \quad (3)$$

where T is the total time for monitoring the seismic situation; N_+ is the number of earthquakes corresponding to the successful forecast for time T ; N is the total number of earthquakes occurred (having spatiotemporal characteristics similar to those predicted) that occurred during time T ; T_{alarm} is the total alarm time (the total duration of all periods of time in which the forecast was valid according to the estimated method during the total monitoring time). The statistical significance of α is determined by the probability of obtaining the J_G efficiency values in the absence of the "earthquake-precursor" relationship. In the absence of such a connection, i.e. at random guessing, the efficiency of J_G is 1. As can be seen from the results

Table 3. Efficiency evaluation of the precursor by A. A. Gusev's method.

Magnitude M	$M \geq 5.0$	$M \geq 5.5$	$M \geq 6.0$	$M \geq 6.5$
N_+	34	14	9	4
N	100	42	17	6
T (day)	1055	1055	1055	1055
T_{alarm} (day)	228	272	282	286
Efficiency J_G	1.57	1.29	1.98	2.46
α	0.003	0.28	0.023	0.049

presented in Table 3, the J_G efficiency takes the highest values for the range of predicted magnitudes $M \geq 6.0$ and $M \geq 6.5$. At the same time, the statistical significance of α , which is 0.023 and 0.049, respectively, demonstrates a low probability of accidental obtaining of such values in the absence of an earthquake connection with the considered precursor.

The efficiency of the precursor J_M by G.M. Molchan's method is defined as

$$J_M = 1 - \nu - \tau \quad (4)$$

where $\tau = T_{\text{alarm}}/T$ is the alarm measure, $\nu = 1 - N_+/N$ is the proportion of target misses. For random prediction $J_M = 0$, and for ideal (without missing target and with zero alarm time) – $J_M = 1$. Table 4 presents the J_M values for the four earthquake threshold magnitudes $M \geq 5.0$, $M \geq 5.5$, $M \geq 6.0$, $M \geq 6.5$. For a high threshold of magnitudes ($M \geq 6.5$), the efficiency of J_M is significantly (almost 3.3 times) higher than for a low threshold ($M \geq 5.0$), which is mainly determined by the change in the reliability of the precursor.

Table 4. Efficiency evaluation of the precursor by G.M.Molchan's method.

Magnitude M	$M \geq 5.0$	$M \geq 5.5$	$M \geq 6.0$	$M \geq 6.5$
τ	0.22	0.26	0.27	0.27
ν	0.66	0.67	0.47	0.33
Efficiency J_M	0.12	0.07	0.26	0.4

Figure 3 shows Molchan's diagrams for the considered magnitude thresholds. In these diagrams the abscissa of the point is defined as a measure of anxiety τ , and the ordinate is defined as the fraction of the passes of the target ν . The diagonal of Molchan's diagram is $\tau + \nu = 1$, connecting points (0;1) (the point of "optimist") and (1;0) (the point of "pessimist") corresponds to a random prediction. For this diagonal, we can construct a confidence interval with a given value α . In this case, only the lower branch of this confidence interval is of interest. As follows from figure 3, the values (τ, ν) obtained for the ranges of magnitudes ≥ 5.0 , $M \geq 6.0$, $M \geq 6.5$ lie under the lower limit of 99% of the confidence interval, which can be interpreted as a high degree of reliability of the revealed connection of the considered precursor with earthquakes of this range of magnitudes occurring at distances up to 500 km from the observation point.

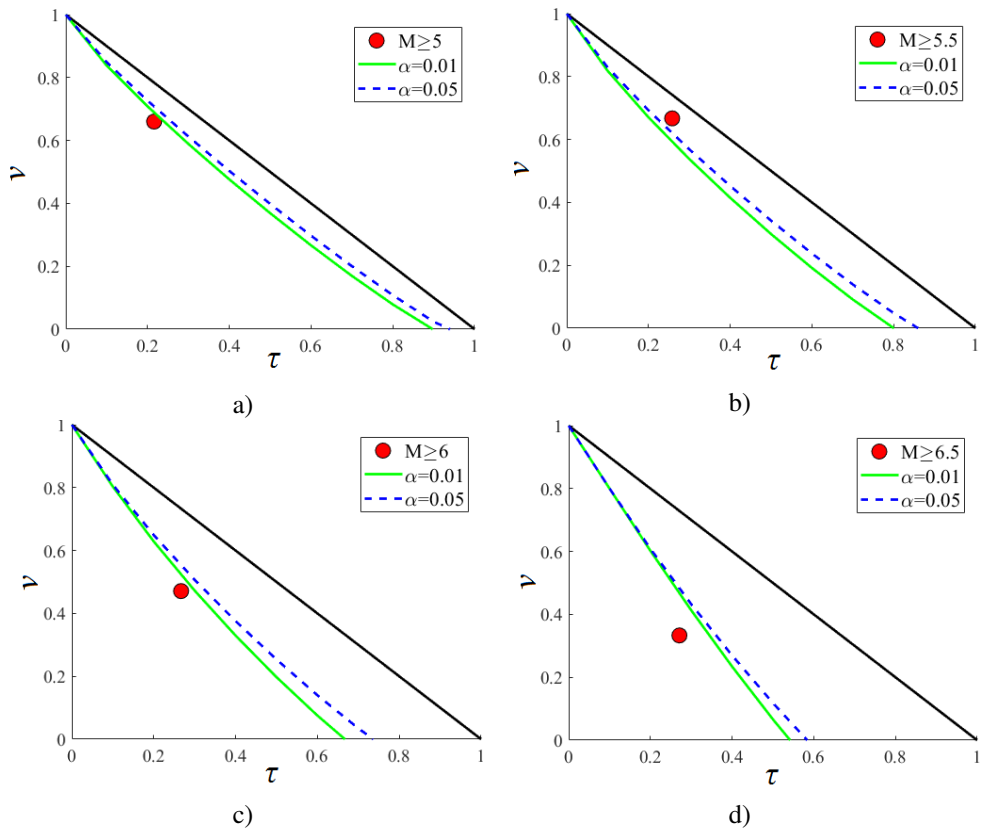


Figure 3. Molchan's diagrams for different thresholds of magnitude M . The lower limits of the confidence interval of the random prediction with the significance level $\alpha = 0.01$ and $\alpha = 0.05$ are marked.

4 Conclusion

The method of short-term prediction of strong earthquakes is presented, in which the excess of the current values of the critical frequency f_oF_2 of the ionospheric layer F2 over the median values during the perturbed state of the magnetosphere, as well as the appearance of ionospheric disturbances: K-layer, Es-spread, F-spread, stratification layer F2, Es type r are considered as precursors. It is shown that the reliability of the forecast increases with the magnitude of the predicted earthquake. When predicting earthquakes with a magnitude $M \geq 6.0$, the reliability is 0.53 (i.e. 53% of earthquakes had a precursor), and the validity is 0.1 (i.e., 10% of the identified anomalies were realized). For earthquakes with $M \geq 6.5$ magnitude, the reliability was 0.67 and the validity was 0.04. The efficiency of the precursor was evaluated in two ways. It is shown that the results of the application of the prognostic method are significantly different from the random guessing and give a gain of almost 2 times for $M \geq 6.0$ and almost 2.5 times for $M \geq 6.5$.

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