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Estimation earthquake occurrence probability in Kamchatka region based on seismological and complex of ionospheric precursors

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Abstract. In this paper the authors present the method of estimation of a region, waiting period and probability of strong earthquakes with $K_S \geq 13.5$ ($M \geq 6.0$) in Kamchatka region based on the combination of mid-term and short-term predictive signs accompanying earthquake formation. The seismological predictive parameter ξ_P was taken as a mid-term precursor. It was calculated on the basis of the probabilistic model of seismic regime. A complex of ionospheric parameters was considered as short-term predictive signs with an earthquake waiting period of up to 5 days. It includes the K-layer, the sporadic Es layer of the r type, the critical frequency foF2, and the frequency stratification of the F2 layer. The probabilities of strong earthquakes with $K_S \geq 13.5$ ($M \geq 6.0$) that occurred over the period 2019–2021 in an expected zone, determined by the parameter ξ_P, were estimated on the basis of Bayes method provided that a complex of anomalous parameters of the ionosphere was identified.

1 Introduction

In [1], the results of ionospheric observations were presented for the purpose of short-term (3–5 days) assessment of the waiting period for Kamchatka earthquakes. At the same time, the application of the theoretical-probabilistic approach to the catalogue of Kamchatka earthquakes [2] allowed to calculate the probability of seismic events entering the seismofocal zone of the Kuril Islands and southern Kamchatka and to establish for it the growth of seismic activity that occurred during 2007–2013. This made it possible to make a medium-term forecast of major earthquakes that occurred in 2013 in this area. The task arises of developing a method for estimation the probability, area and time period of expectation of strong Kamchatka earthquakes with an energy class of $K_S \geq 13.5$ ($M \geq 6.0$) based on the joint of seismological and ionospheric prognostic signs based on the combination of seismological and ionospheric prognostic signs. This work is devoted to the solution of this problem.

2 Method of calculation of seismological precursor of earthquakes

Application of A. N. Kolmogorov's axiomatics to the catalogue of seismic events allows to consider each earthquake as an elementary event ω_i , and the whole catalogue or its separate

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part as a space of elementary events Ω [2]. Each elementary event ω_i can be characterized by four random variables $\xi_i(\omega_i) = \varphi_i(\omega_i), \lambda_i(\omega_i), h_i(\omega_i), K_i(\omega_i)$, where quantities φ_i, λ_i, h_i are the coordinates of the earthquake, and K_i – energy class. (Event time $t_i(\omega_i)$, as having no mathematical expectation, is excluded from the system of random variables, but it is taken into account as a parameter that determines the occurrence of the event ω_i in the period under study ΔT). For a set of seismic events that occurred over a period of time ΔT, the probability space is a collection of three objects $\{\Omega, \tilde{F}, P\}$, where Ω – space of elementary events , $\tilde{F}$ – set of subsets of random events, P – probabilities of these events. Random events (for a specific selected period of time ΔT) can represent an arbitrary combination of a variable number of random variables (when fixing others) and form some in $\tilde{F}$ subsets A, B, C and etc.

The probability that a seismic event will fall within the specified intervals: latitude $\Delta\varphi = \varphi_i - \varphi_{i-1}$, longitude $\Delta\lambda = \lambda_j - \lambda_{j-1}$, depth $\Delta h = h_m - h_{m-1}$ and energy class $\Delta K = K_n - K_{n-1}$

$$\begin{aligned} P(\Delta\varphi_i, \Delta\lambda_j, \Delta h_m, \Delta K_n) &= \int_{\varphi_{i-1}}^{\varphi_i} d\varphi \int_{\lambda_{j-1}}^{\lambda_j} d\lambda \int_{h_{m-1}}^{h_m} dh \int_{K_{n-1}}^{K_n} f(\varphi, \lambda, h, K) dK = \\ &= F(\varphi_i, \lambda_j, h_m, K_n) - F(\varphi_{i-1}, \lambda_{j-1}, h_{m-1}, K_{n-1}) = \\ &= P(\Delta\varphi_i) P(\Delta\lambda_j|\Delta\varphi_i) P(h_m|\Delta\varphi_i, \Delta\lambda_j) P(K_n|\Delta\varphi_i, \Delta\lambda_j, h_m) \end{aligned} \quad (1)$$

where i, j, m and n – indices corresponding to intervals of random variables. Statistical processing of the catalog by the formula (1) makes it possible to calculate not only the average probability of occurrence of a seismic event in a given interval of geographical coordinates, depth and energy class through the corresponding conditional probabilities, but also to obtain numerical values of the step distribution function $F(\Delta\varphi, \Delta\lambda, \Delta h, \Delta K)$. As the number of events n increases and the interval Δ decreases, the relative frequency υ tends to its mathematical counterpart P, and $F(\Delta\varphi, \Delta\lambda, \Delta h, \Delta K)$ – towards sustainable continuous distribution $F(\varphi, \lambda, h, K)$.

The random event A on the basis of which the seismological precursor was calculated: «Hit of epicenters of seismic events that occurred in the selected volume V, in the specified intervals of latitude $\Delta\varphi$ and longitude $\Delta\lambda$». The catalogue of earthquakes of Kamchatka Branch of Federal Research Center "United Geophysical Service RAS" during 1962–2021 was used for the analysis.

The studied seismically active area S located along the Eastern coast of Kamchatka, including the Continental regions of Kamchatka, the Southern and Northern seismofocal zones is divided into $m = 12$ non-overlapping areas with dimensions of $S_i = 150 \times 200$ km (Fig. 1). Since seismic events with energy class $K_S^{\mathrm{pr}} \geq 13.5$ are considered as predicted earthquakes in this paper, consequently, according to [3] the length of the gap in the focus of such earthquakes is $L \geq 11$ km. Assuming that the linear size of the earthquake preparation area is of the order of 10 rupture lengths, i.e. 110 km, the spatial cell size of 150×200 km can be chosen as the base case for calculations.

For each square S_i $(i = \overline{1, m})$ in a moving time window ΔT_k passing with step Δt, the time interval $T = 1962 - 2021$ calculates the probability of seismic events $P_k(S_i) = n_{ik}/N_k$, where n_{ik} – number of seismic events with energy class $K_S \geq 9.0$ and the depth of the hypocenter is less 200 km, occurred in the area of S_i for the period ΔT_k, $N_k = \sum_{k=1}^{m} n_{ik}$ – total number of earthquakes with $K_S \geq 9.0$ and with the same hypocenter depth, took place on the square $S = \sum_{i=1}^{m} S_i$ during ΔT_k. Also in each region S_i long-term (background) values of probability of seismic events hit are calculated $P_T(S_i) = n_{iT}/N_T$, where n_{iT} – number of seismic events with energy class $K_S \geq 9.0$, occured during T, $N_T = \sum_{k=1}^{m} n_{Tk}$ – total number of earthquakes with $K_S \geq 9.0$, occurred during T on the square S. In this paper, the size of the time window and its offset step are set equal, respectively $\Delta T_k = 1$ year and $\Delta t = 1$ day, a time interval at

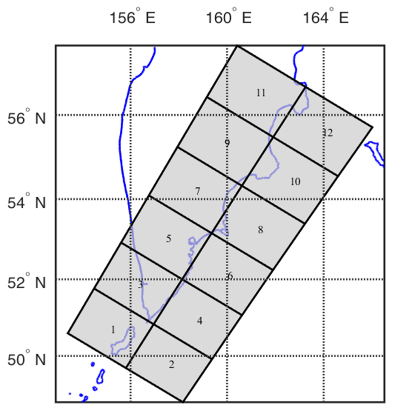

Figure 1. Division of the studied seismic area S into unit cells S_i with dimensions of 150×200 km.

which the study of the seismic regime is equal to $T = 1962 - 2021$. On Fig. 2, as an example, the values of probabilities of seismic events in the region S_2 are presented.

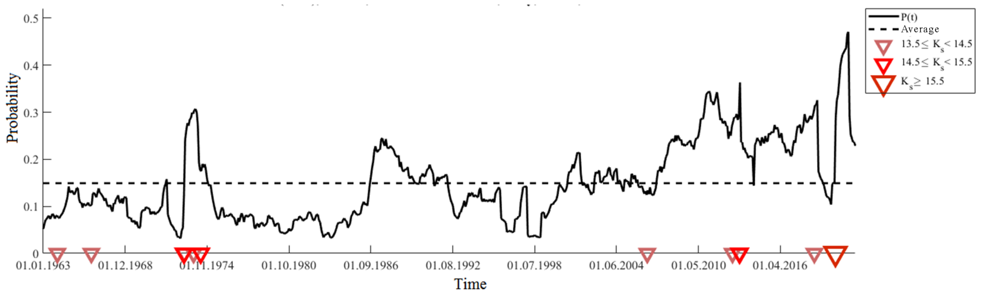

Figure 2. Time series of probability values $P_k(S_2)$. Red triangles on the time axis indicate earthquakes with $K_S \geq 13.5$ ($M \geq 6.0$).

To obtain statistically significant deviations of the current probability values $P_k(S_i)$ from their long-term (background) values $P_T(S_i)$ the parameter ξ_P, is used, determined on the basis of [4] and presented as:

$$\xi_P = \begin{cases} \frac{\Delta P_k - sign(\Delta P_k)\cdot|\sigma_{P_k}|}{|\sigma_{P_T}|}, & \text{if } |\Delta P_k| > |\sigma_{P_k}| \\ 0, & \text{if } 0 \leq |\Delta P_k| \leq |\sigma_{P_k}| \end{cases} \tag{2}$$

where P_k and $\sigma_{P_k} = \sqrt{(P_k(1 - P_k)/n_k}$ current probability values and its standard deviation in the sliding time window ΔT_k; P_T and $\sigma_{P_T} = \sqrt{P_T(1 - P_T)/n_T}$ long-term probability values and standard deviation $T > \Delta T_k$; n_i and n_T – the number of seismic events that occurred over time periods, respectively ΔT_k and T; $\Delta P_k = P_k - P_T$ the difference between the current P_k probability value and the long-term probability value P_T. Fig. 3 presents the timing values parameter ξ_P for region S_2.

Strong earthquakes can be preceded by periods of increased seismic activity (an increase in the number of background events), and periods of weakening of seismic activity (a decrease in the number of background events). When you search for periods of enhanced seismicity

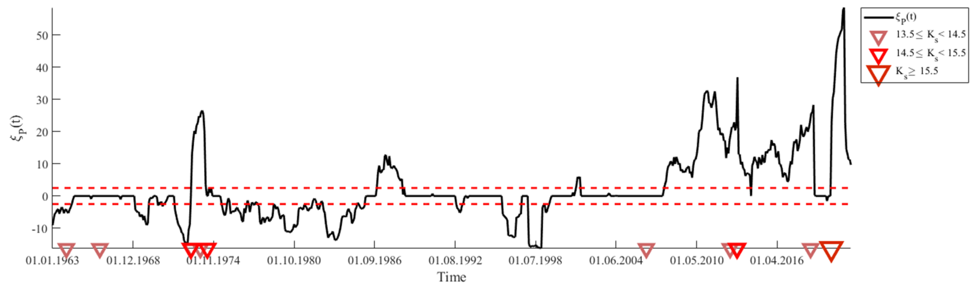

Figure 3. Temporary values of the parameter ξ_P for region S_2. Red triangles on the time axis indicate earthquakes with $K_S \geq 13.5$ ($M \geq 6.0$).

Table 1. Predictive efficiency of the parameter ξ_P.

Type of seismic anomaly	V	R	J_G	J_M
Seismic activity ($\xi_P \geq 2.5$)	0.57	0.49	1.47	0.15
Seismic calm ($\xi_P \leq -2.5$)	0.51	0.52	2.15	0.28
Seismic activity and calm	0.45	0.76	1.47	0.24

in the beginning of the anomaly in the parameter ξ_P is taken as the time of appearance of the values $\xi_P \geq \xi_P^a$, where ξ_P^a – anxiety level is selected experimentally. In the case of searching for periods of seismic calm, the beginning of the anomaly is identified by the moment of occurrence of the values $\xi_P \leq \xi_P^c$, where ξ_P^c – anxiety level is selected experimentally. Accordingly, when $\xi_P^c < \xi_P < \xi_P^a$ it is assumed that the current probability values do not significantly deviate from the background values. In this paper, the values of the criteria for the periods of activation and lull were established respectively $\xi_P^a = 2.5$ and $\xi_P^c = -2.5$.

To assess the prognostic effectiveness of a prognostic feature ξ_P following parameters are used: ratio of the number of earthquakes for which the precursor was allocated to the number of all earthquakes (reliability R), ratio of the number of precursor anomalies to the total number of isolated anomalies (validity V) [5], the effectiveness of A. A. Gusev [6] and G. M. Molchan's [7] methods.

The results of the evaluation of the predictive efficiency of parameter ξ_P for earthquakes with $K_S \geq 13.5$ are presented in Table 1 and errors diagram (Fig. 4).

As can be seen from Table 1, the share of anomalies of seismic regime activation identified by parameter ξ_P and preceding earthquakes (parameter V) was 57%, and the share of calm anomalies was 51%. The relative number of anomalies of the seismic regime of both types preceding the onset of earthquakes with $K_S \geq 13.5$, was 45%. The activation of the seismic regime was preceded by 49% of earthquakes, and calm – 52%. The J_G prediction efficiency for both types of anomalies was 1.47. Since $J_G > 1$, this predictive feature is considered informative and can be used in earthquake prediction algorithms. The J_M prediction efficiency for both types of anomalies was 0.24 and as can be seen from the error diagram (Fig. 4) the values (τ, ν) lie below the lower limit of 99% of the confidence interval (green curve), which can be interpreted as a high degree of reliability of the revealed connection between the identified anomalies of the seismic regime using the parameter ξ_P and predicted earthquakes from the considered range of the energy class.

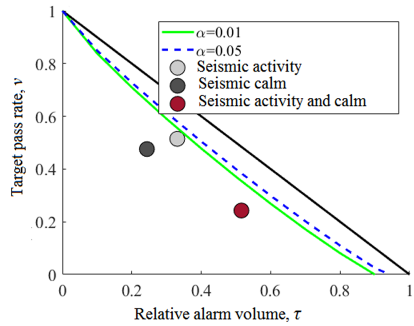

Figure 4. The diagram of errors for the parameter ξ_P in predicting earthquakes with $K_S \geq 13.5$. The lower bounds of the confidence interval of the random forecast with the significance level are marked $\alpha = 0.01$ and $\alpha = 0.05$.

Table 2. The predictive efficiency of the complex ionospheric precursors.

$n(E_A)$	$n(E)$	$n(A_E)$	$n(A)$	V	R	J_G	τ	ν	J_M
24	30	21	180	0.1	0.8	1.69	0.47	0.2	0.33

3 Method of short-term earthquake prediction based on the complex of ionospheric parameters

In this work the data of radiophysical observations made by means of vertical radiosonding are used. The automatic ionospheric station (AIS) of vertical radiosonding is located in the village of Paratunka ($\varphi = 52.97°$ N, $\lambda = 158.24°$ E). Observations are made once every 15 minutes in pulse mode at frequencies from 1 to 15 MHz.

The ionospheric precursors with an earthquake expectation period of up to 5 days were considered in article [8]. On the basis of the selected most effective ionospheric precursors, an algorithm for short-term earthquake prediction was constructed, in which a joint analysis of the ionospheric disturbances under consideration is carried out in a sliding time window of width $\Delta T = 5$ days with a step $\Delta t = 1$ day. The condition for announcing the start of the waiting period to seismic event was the execution in a time interval ΔT for at least three of the four ionospheric parameters consider the following criteria:

- K-layer formation during at least one day of ΔT interval;
- Formation of sporadic layer Es type r for at least one day interval ΔT.
- Exceeding the critical frequency foF2 layer F2 median values f_{med}, calculated for the previous 30 days, not less than 20% ($\frac{f\text{oF2}-f_{\text{med}}}{f_{\text{med}}} \geq 0.2$) against the background of the development of the magnetospheric storm (total values of the K-index per day $\Sigma K \geq 20$);
- Stratification of the F2 layer in frequency (mode "V") for at least one day interval ΔT;

The waiting period is chosen equal to $T_{\text{w}} = 5$ days. The algorithm was evaluated its predictive effectiveness in a time interval 01.01.2013–01.06.2021 for seismic events $K_S \geq 13.5$ ($M \geq 6.0$) at depths of 100 km in radius $r = 500$ km from the registration point of the ionospheric observations.

According to the results presented in Table 2, when predicting earthquakes with energy class $K_S \geq 13.5$, the reliability is 0.8 (i.e. 80% of earthquakes had a precursor), and the reliability is 0.1 (i.e. 10% of detected anomalies were realized). The efficiency value $J_G = 1.69$

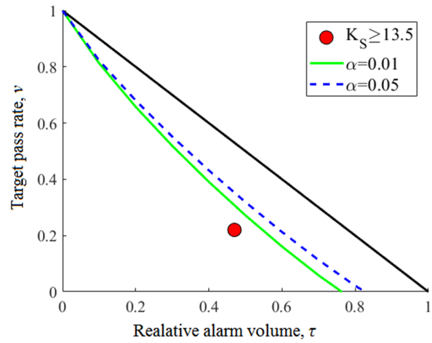

Figure 5. The diagram of errors for the algorithm of the complex ionospheric precursors for $K_S \geq 13.5$.The lower bounds of the confidence interval of the random forecast with the significance level are marked $\alpha = 0.01$ and $\alpha = 0.05$.

shows that the prognosis by this method is statistically significant and 1.69 times different from random guessing. In the error diagram (Fig. 5) the values (τ, ν) obtained for the range $K_S \geq 13.5$ lie below 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 complex of ionospheric precursors with earthquakes of this range of energy class that occurred at distances up to 500 km from the observation point.

4 Method to estimate earthquake occurrence probability

The method to estimate the region, waiting time period and probability for earthquake with $K_S \geq K_S^{\mathrm{pr}}$ (K_S^{pr} – is the minimum energy class of the predicted earthquakes) based on a joint analysis of the seismic parameter ξ_P and a complex of ionospheric precursors can be presented as follows:

1. Monitoring of the seismic regime in elementary cell S_i based on the seismological parameter ξ_P. Area of expectations of strong earthquake will be considered $S_{\exp}$, which includes the unit cells, which was identified anomalies of seismic regime parameter ξ_P: $S_{\exp} = \frac{1}{l}\sum_{j=1}^{l} S_j$, where $l \leq m$ – number of areas where abnormal parameter values are identified ξ_P. The average waiting period for a strong earthquake will be considered the period $\tilde{T}_{\mathrm{w}} = \frac{1}{l}\sum_{j=1}^{l} T_j^{\mathrm{w}}$, where l – number of areas where abnormal parameter values are identified ξ_P, $T_j^{\mathrm{w}} = \tilde{T}_j^{\mathrm{w}} + \sigma_T$ – the waiting period earthquake in the cell S_j, $(j = \overline{1, l})$;

2. Monitoring of the ionospheric disturbances under consideration in a sliding time window of width $\Delta T = 5$ days with a step $\Delta t = 1$ day.

3. If the appearance of at least three of the four ionospheric parameters is recorded in the time interval ΔT, then using formula 3, the conditional probability $P(D_1|EI)$ of the onset of an earthquake in the area of expectations of strong earthquake $S_{\exp}$ is calculated.

4. If the probability $P(D_1|EI)$ exceed the specified criterion, then in the area $S_{\exp}$, the waiting period T_{w} of a strong earthquake with a duration of 5 days is announced. The

waiting period T_w can be extended if the complex of ionospheric precursors has been registered again.

The probability of occurrence of a seismic event with $K_S \geq K_S^{\text{pr}}$ in the range S_{exp} (random event D_1), provided that anomalies of the seismic regime are identified in it (random event E), as well as a complex of ionospheric precursors (random event I), calculated based on the Bayes formula:

$$P(D_1|EI) = \frac{P(D_1) \cdot P(E|D_1) \cdot P(I|D_1)}{P(D_1) \cdot P(E|D_1) \cdot P(I|D_1) + P(D_2) \cdot P(E|D_2) \cdot P(I|D_2)} \tag{3}$$

The random event D_1 – an earthquake occurrence predicted energy class $K_S \geq K_S^{\text{pr}}$ in the range S_{exp}.

The probability of this event is defined as $P(D_1) = \frac{n_l}{N}$, where $n_l = \sum_{j=1}^{l} n_j$ – the number of earthquakes with $K_S \geq K_S^{\text{pr}}$ that occurred in the S_{exp} area during the observation period T_1, N – the number of earthquakes with $K_S \geq K_S^{\text{pr}}$ that occurred in the $S = \sum_{j=1}^{m} S_j$ area during the observation period T_1 of parameter ξ_P.

The random event D_2 – absence of earthquake with energy class $K_S \geq K_S^{\text{pr}}$ in area S_{exp}. The probability of this event D_2 is $P(D_2) = 1 - P(D_1)$.

The random event E – the occurrence of anomalous values of the parameter ξ_P.

The random event I – the occurrence of complex of the ionospheric precursors. Then the events E and I can be represented in the form: $EI = D_1EI + D_2EI$

The random event D_1EI – the occurrence of earthquake with $K_S \geq K_S^{\text{pr}}$ in area S_{exp} upon identification of an anomaly of the seismic regime (activation or calm) and the appearance of a complex of ionospheric precursors. The probability of this event is defined as $P(D_1EI) = P(D_1) \cdot P(EI|D_1) = P(D_1) \cdot P(E|D_1) \cdot P(I|D_1)$.

The probability $P(E|D_1) = \frac{n_{\text{pr1}}}{N_{S_{\text{exp}}}}$ is earthquakes occurrence probability with $K_S \geq K_S^{\text{pr}}$ in area S_{exp} when identifying seismic anomalies; n_{pr1} – number of earthquakes with $K_S \geq K_S^{\text{pr}}$, predicted when anomalies of the seismic regime appear over period T_1; $N_{S_{\text{exp}}}$ – total number of earthquakes with $K_S \geq K_S^{\text{pr}}$ in area S_{exp} over period T_1.

The probability $P(I|D_1) = \frac{n_{\text{pr2}}}{N_{S_{\text{exp}}}}$ is earthquakes occurrence probability with $K_S \geq K_S^{\text{pr}}$ in area S_{exp} when identifying the complex of ionospheric disturbances; n_{pr2}– number of earthquakes with $K_S \geq K_S^{\text{pr}}$, predicted when an ionospheric anomalies appears during the observation period T_2 (T_2 is a registration period of ionospheric parameters); $N_{S_{\text{exp}}}$ – total number of earthquakes with $K_S \geq K_S^{\text{pr}}$ in area S_{exp} over period T_2.

The random event D_2EI – absence of earthquake with energy class $K_S \geq K_S^{\text{pr}}$ in area S_{exp} when identifying anomalies of the seismic regime (activation or calm) and appears complex of ionospheric precursors. The probability of this event is defined as $P(D_2EI) = P(D_2) \cdot P(EI|D_2) = P(D_2) \cdot P(E|D_2) \cdot P(I|D_2)$.

The probability $P(E|D_2) = \frac{n_{\text{fa1}}}{N_{\text{a1}}}$ is probability of occurrence of abnormal parameter values ξ_P (false alarms) in the area S_{exp}, which did not end with $K_S \geq K_S^{\text{pr}}$ earthquakes; n_{fa1} – number of false alarms per observation period T_1; N_{a1} – the total number of cases of abnormal behavior of the parameter ξ_P in the area S_{exp} over the period T_1.

The probability $P(I|D_2) = \frac{n_{\text{fa2}}}{N_{\text{a2}}}$ is probability of occurrence of ionospheric anomalies complex, which did not end with earthquakes; n_{fa2} – number of false cases of the appearance of a complex of ionospheric parameters per observation period T_2; N_{a2} – the total number of occurrences of a complex of ionospheric parameters over the period T_2.

Table 3. List of predicted earthquakes with energy class $K_S \geq 13.5$ ($M \geq 6.0$) over period 01.01.2019–01.06.2021.

№	Date EQ	K_S	$P(D_1 \vert EI)$	S_{exp}	T_{w}
1	2019.06.25	14.3	0.69	+	2019.06.21–2019.06.26
2	2019.06.26	14.4	0.69	+	2019.06.21–2019.06.26
3	2020.01.22	14.3	0.71	+	2020.01.21–2020.02.05
4	2020.02.20	14.3	0.72	+	2020.02.11–2020.02.29
5	2020.03.25	16.8	0.73	+	2020.03.19–2020.03.28
6	2021.03.16	14.6	0.74	+	2021.02.14–2020.03.30

5 Retrospective predictive estimates of the area, period and probability of earthquake occurrence with $K_S \geq 13.5$

In the considered seismically active region, 6 earthquakes with an energy class of $K_S \geq 13.5$ ($M \geq 6.0$) occurred during the period 01.01.2019–01.06.2021. The results of the retrospective analysis according to the proposed method are presented in Table 3. Signs "+" and "-" observed earthquake respectively inside the waiting area S_{exp} and outside its borders. All six seismic events occurred during the waiting periods T_{w}, determined from the complex of ionospheric parameters, and hit into the waiting area S_{exp}, determined from the values of the parameter ξ_P. The conditional probability $P(D_1|EI)$ of earthquake occurrence ranged from 0.69 to 0.74.

Figure 6a shows, as an example, the waiting area for the earthquake of 25.03.2020 with $K_S = 16.8$, constructed on 19.03.2021 based on the analysis of the anomalous values of the parameter ξ_P.

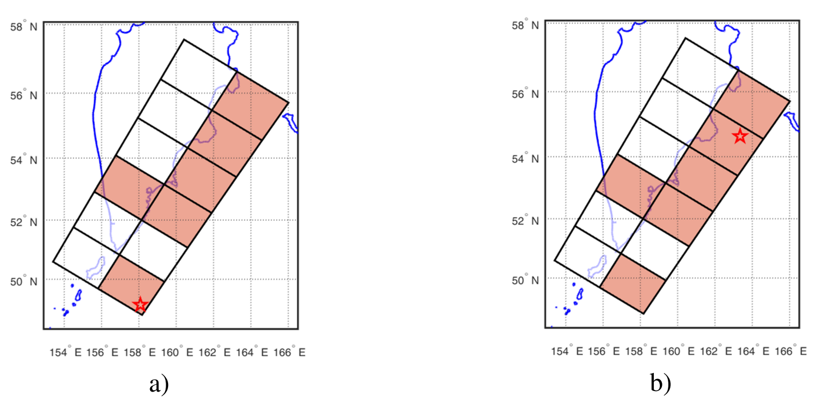

Figure 6. Maps of expectation area S_{exp} for earthquakes: a) 25.03.2020, $K_S = 16.8$; b) 16.03.2021, $K_S = 14.6$. Red stars on the map are earthquake epicenters.

The results of evaluating the effectiveness of earthquakes prediction with $K_S \geq 13.5$ for the time period 01.01.2019–01.06.2021, when choosing as the alarm level the values of the conditional probability $P(D_1|EI) = 0.5$ and $P(D_1|EI) = 0.7$, are presented in Table 4 and on the error diagrams (Fig. 7).

The analysis of the predictive efficiency of the presented method showed that at $P(D_1|EI) \geq 0.5$ its reliability $R = 1$ (100% of earthquakes were predicted), validity $V = 0.09$ (9% of forecasts ended with earthquakes), efficiency J_G was 1.8 (with $J_G = 1$, the forecast

Table 4. The effectiveness for the method of earthquakes prediction with $K_S \geq 13.5$ for chosen levels of the conditional probabilities $P(D_1|EI)$.

Levels of conditional probability $P(D_1|EI)$	V	R	J_G	J_M
0.5	0.09	1	1.8	0.44
0.7	0.09	0.67	1.52	0.23

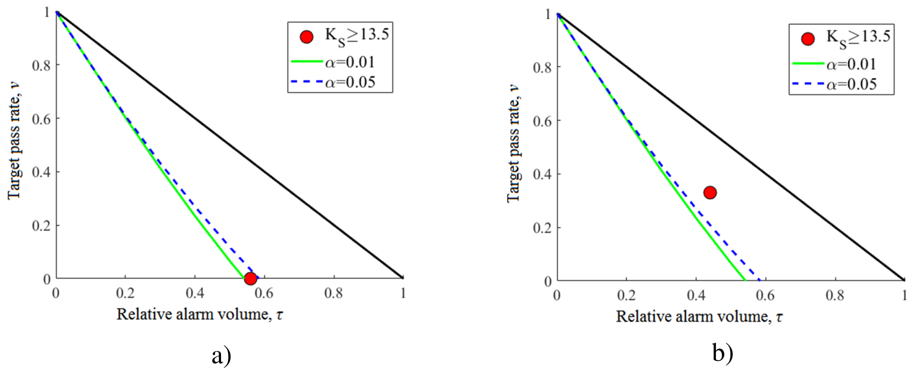

Figure 7. The diagram of errors for the method of earthquakes prediction with $K_S \geq 13.5$ ($M \geq 6.0$) based on joint analysis of seismological and complex of ionospheric precursors for chosen levels of the conditional probabilities $P(D_1|EI) = 0.5$ (a) and $P(D_1|EI) = 0.7$ (b).

is considered random). The efficiency J_M was 0.44, which indicates the presence of a connection between the considered complex of precursors and earthquakes with an energy class $K_S \geq 13.5$ ($M \geq 6.0$).

6 Conclusion

An approach is presented that combines seismological and ionospheric prognostic signs in order to assess the probability of occurrence of earthquakes with $K_S \geq 13.5$ ($M \geq 6.0$) in the Kamchatka region. A retrospective analysis was carried out using this technique for the time period 01.01.2019–01.06.2021.

The effectiveness of method for estimation the area and possible period of the occurence of seismic events with $K_S \geq 13.5$ in the joint analysis of the seismic parameter ξ_P and the complex of ionospheric precursors (at the values of the conditional probability of the onset of earthquakes $P(D_1|EI) \geq 0.5$ and $P(D_1|EI) \geq 0.7$) shows that the forecast using this method is more than 1.5 times different from a random guess.

The low validity of the V forecast may be due to the fact that, ionospheric disturbances are formed against the background of solar activity, and it is not yet possible to accurately indicate the lower threshold of the earthquake magnitude, the preparation of which is already beginning to influence the state of the ionosphere. Seismic events with an energy class $K_S \geq 13.5$ predicted by ionospheric precursors and taken into account in statistics do not include events with an energy class $K_S < 13.5$, although the ionospheric precursor has formed. Consequently, the ionospheric forecast signs that precede seismic events with $K_S < 13.5$ are false for events with $K_S \geq 13.5$, thereby lowering the forecast reliability.

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