TRANSLATION
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Mid-term assessments of seismic hazards on Sakhalin Island using the LURR method: new results

© 2020 *Aleksander S. Zakupin*, Nataliya V. Boginskaya*

Institute of Marine Geology and Geophysics, FEB RAS, Yuzhno-Sakhalinsk, Russia
**E-mail: a.zakupin@imgg.ru*

Abstract. A retrospective analysis of seismic regime in the central part of Sakhalin Island within the period from 1997 to 2005 by the LURR (load/unload response ratio) method is presented. Estimates were not earlier conducted for the outlined period due to a lack of data in the rated sampling of this part of the island. In the present work, additional information from two independent catalogues is adduced. Seismicity behaviour prior to the Uglegorsk earthquake of 4 August 2000 (Mw = 6.7) was considered according to the LURR method. This earthquake was up till now considered as a missed target in the series of 7 predictive assessments of Sakhalin earthquakes having a magnitude above 5.5. The computation results revealed the LURR parameter anomaly to be a precursor, on which basis the location and time of the conditionally predictable event were accurately determined. The LURR parameter anomaly was noted in the rated area in the February of 2000, 6 months prior to the earthquake's occurrence.

Keywords: seismicity, seismic events, LURR method, earthquake precursor, retrospective analysis.

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Introduction

In the last few years, the staff of the Institute of Marine Geology and Geophysics of FEB RAS (IMGG FEB RAS) obtained a number of interesting results in the field of mid-terms assessments of the seismic hazard for the earthquakes with Mw > 5.5 on Sakhalin. The anomalies in the rated parameter distributions (the value deviates from the basic, that equals 1), i.e. the earthquakes precursors [Zakupin et al., 2018; Zakupin, Semenova, 2018], were revealed by the LURR method [Yin et al., 2000; Yangde et al., 2012] in six zones of the island during the period from 1998 to 2019.

In the primary source [Yin X., Yin C., 1991; Yin et al., 2000] the LURR method associates an anomaly appearance with preparing of an earthquake with a magnitude above the upper bound of a rated sampling within the estimated area. At that the lower bound of the rated sampling is set arbitrarily to cut off the weak – background seismicity. But the upper bound shows the magnitude of an expected earthquake (mainshock). Both these thresholds are chosen subject to the character of the regional seismicity. We have found experimentally that when calculating for Sakhalin the lower bound M = 3.3, and the upper one – 5.0 can be chosen as admissible variations. At the same time the revealed anomalies agree well with the earthquakes with M > 5.5. The researchers [Yin et al., 2000; Yangde et al., 2012] note that the alarm period may amount from two to several years since

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the detection moment, and the earthquake must occur in the estimated area (a linear dimension is 100 km).

The strong seismic events occurred on Sakhalin in all six revealed zones during no more than 2 years after the anomalies appearance. In four cases the anomalies were determined after the occurred earthquakes (in retrospect), and two from six zones were revealed in the mode of operative computing (conducted from 2015). It allowed to make two official predictions of the Onor (2016, Mw = 5.8) and the Krilyon (2017, Mw = 5.0) earthquakes [Zakupin et al., 2018; Zakupin, Semenova, 2018]. The predictions were considered on the sessions of Sakhalin Branch of Russian Expert Committee on Emergency Situations. Both predictions were recognized to be fully realized, although there were small deviations on source location for the Onor earthquake (at the end of predicted area) [Zakupin et al., 2018] and on magnitude for the Krilyon (Mw = 5.0). According to the data of three seismic catalogs used for estimates [Zakupin et al., 2018], there were seven earthquakes with Mw > 5.5 on the island for last 30 years: Neftegorsk (1995, Mw = 7.2), Uglegorsk (2000, Mw = 6.7), Piltun (2005, Mw = 5.6), Gornozavodsk (2006, Mw = 5.6), Nevelsk (2007, Mw = 6.2), Uanga (2010, Mw = 5.7) and Onor (2016, Mw = 5.8).

The catalog of IMGG FEB RAS stations network [Stepnov et al., 2014] was used in the computations for the north part of the island mainly from 50.0° to 54.0° N. This catalog was formed and supported by the laboratory of earthquake physics of the IMGG FEB RAS on the base of data of six stations (one of them, in the Oha city, had belonged to the Sakhalin Branch of the Federal Research Center "United Geophysical Survey of the RAS" (SB FRC UGS RAS)). We previously used the IMGG FEB RAS catalog for estimates due to its greater availability and populating operability, despite the SB FRC UGS RAS also formed a seismic catalog on the territory, covered with the IMGG FEB RAS network. Two zones with the anomalies were revealed with its help in 2008 and 2015. Notice that the anomaly of 2008 was weak enough – the parameter slightly exceeded the value of 2 [Zakupin et al., 2018]. The anomaly preceded the Uanga earthquake in the March of 2010, and the zone with anomaly well-nigh coincided with the earthquake epicenter. The second anomaly was significant (five times the threshold exceeding), but the center of the estimated zone was shifted in regards to the epicenter of realized prediction (Onor earthquake) for 1° northward and 0.5° eastward.

For retrospective estimates during the period from 1998 to 2005, we used the catalog of Sakhalin Island earthquakes for 1905–2005 [Poplavskaya et al., 2006]. By the data of this catalog, in 1998–2005 the number of seismic events in the range of working sampling $3.3 \leq M \leq 5.0$ over all parts of the island was insufficient to carried out the statistically significant computations, that highly reduces the degree of confidence in obtained results. However, because the most powerful seismic event on Sakhalin – the Neftegorsk earthquake of 1995 (Mw = 7.2) – was registered in the north of the island, the computations for the northern part of the island were carried out with this catalog (due to lack of other for that period).

The data analysis on the territory northward of 51.0° N revealed two zones of the seismic hazard in 1993 and 2004 located not far from each other – the zones of Neftegorsk and Piltun earthquakes. In spite of concerns, deficiency of rated events did not bring to false signs detection [Zakupin et al., 2018].

The catalog of SB FRC UGS RAS was used for estimates on the southern part of the island from 2003 to 2019. These data allowed to reveal a precursor of the Nevelsk earthquake in the May of 2007 [Zakupin et al., 2018], as well as to make the operative prediction in the area of Krilyon peninsula after the anomaly had been detected in 2016 [Zakupin, Semenova, 2018]. Both earthquakes occurred in the pointed zones, but the Krilyon earthquake in 2017 had a magnitude of 5.0, that was lower than expectation threshold of 5.5 that we set. In view of conventionality of this threshold (a magnitude determination by the sampling boundaries) this prediction is considered as realized.

In whole the statistics on Sakhalin appeared to be impressive, because only two strong earthquakes from eight (including the Krilyon one) had no anomalies, detected using the LURR method – the Uglegorsk (04.08.2000, Mw = 6.7) and the Gornozavodsk (17.08.2006, Mw = 5.6). The reasons in both cases are different. Computations on the Gornozavodsk earthquake have been conducted, but a precursor is not revealed, while the Uglegorsk event for that period and zone (49–51° N) has not been estimated due to shortage of data in the catalog [Poplavskaya et al., 2006]. However, a precursor of the Neftegorsk earthquake was obtained just by this catalog, which covered the period needed for estimates, and the Uglegorsk earthquake magnitude Mw = 6.7 was a little lower than the magnitude of the Neftegorsk (Mw = 7.2). Its «neglect» is more likely reasoned with absence of victims (only constructions damages have been registered). But in the statistics of estimates on Sakhalin this gap is desirable to be filled, using such volume of seismological information as possible. For this purpose, the SB FRC UGS RAS catalog was created. It has begun forming since 1997, and broadened constantly, covering all of the island. Owing to that, the result of processing by the regional catalog [Poplavskaya et al., 2006] can be confronting with the result by this catalog to take an expert decision on anomalies.

This work aims to conduct the computations on precursors detection in the zone of the Uglegorsk earthquake by the LURR method, and to demonstrate successful result by applied method, or to confirm current status of this earthquake as missed target.

Methodology

The LURR method was worked out by Chinese seismologists in the1990-s [Yin X., Yin C., 1991; Yin et al., 1995]. The abbreviation meaning is «load/unload response ratio». Briefly, the method essence is in the following [Zakupin et al., 2018; Zakupin et al., 2020]. The method bears upon the consistent models of the elasticity theory (the model of perfectly rigid earth) and the fracture mechanics (the Mohr-Coulomb criterion). The main idea is that behind the limits of elastic deformation of the medium response to load does not correspond to response to unload. In the course of time this mismatch just becomes stronger – right up to loss of a failed object stability. The method supposes solving of the elasticity theory equations to determinate the stress tensor components on the plane, where the slip vector is located. The estimates are carried out for each earthquake in the catalog. In doing so, the shifts due to tidal affect in the specified point are taken into account. Lunar-solar tides using in the method is justified with the fact, that it is impossible to find another such ideal calibrated indicator of load/unload in the geological medium. Tectonic and lithostatic components are not taken into consideration, because their variation rates differ by orders of magnitude from the tidal. The Mohr–Coulomb criterion computation is carried out to separate earthquakes into «loading» and «unloading» ones. If an earthquake has occurred when this criterion value increasing, it is defined as «positive», in the contrary case – as «negative». The studied parameter (LURR) is identified with the ratio of the total Benioff deformation of the all positive earthquakes to the all negative ones for some time interval (in mathematical processing it is a value of running window). In elastoplastic mediums the yield phenomenon is observed prior the failure, when deformation continues to grow at constant stresses. It is apparent, that, at this state of things, the computations of the ratio of a response to load to a response to unload has no sense (there is not a reaction, as such), and mathematically the LURR parameter becomes close to 1 again. In the zone of transition from elastic deformation to inelastic this parameter begins growing and reaches its maximum values near the medium failure. That is why the main (predicted) event may be expected in the medium, where brittle fracture is realized, after the curve have reached the maximum values. At the same time in the medium, where appearance of the plastic effects is possible, the parameter returns to the background level and some time lag appears (the lag since the moment of prediction sign detection, an anomaly – the LURR variation). Probably, this lag depends on geological conditions, however this relation cannot be understood yet. The methodology of estimates by the LURR method is described in detail in the original works [Yin X., Yin C., 1991; Yin et al., 1995; Yin et al., 2000], as well in the works of researchers, who has applied this method [Zakupin et al., 2018, 2020; Yangde et al., 2012; et al.].

We have applied the Seis-ASZ software suite worked out in the IMGG FEB RAS for computations using the LURR method with the setting of the parameters, which are standard for our estimates: window – 360 days, shift – 30 days, range of the magnitudes – 3.3–5.0 [Zakupin et al., 2018].

Initial materials

The estimates by the LURR method for the central part of the island, including the area, where the Uglegorsk earthquake had occurred, were conducted by two catalogs: «Regional catalog of Sakhalin Island earthquakes, 1905–2005» [Poplavskaya et al., 2006] and the catalog of SB FRC UGS RAS presented in the press with the annual issues (for example, [Fokina et al., 2019]). We will label them the catalogs no. 1 and no. 2 for the sake of convenience.

The first catalog covers the period from 1905 to 2005 and contains more than 3500 seismic events over Sakhalin Island. The catalog no. 2 includes the earthquakes of all the regions of the Northern Eurasia for the instrumental

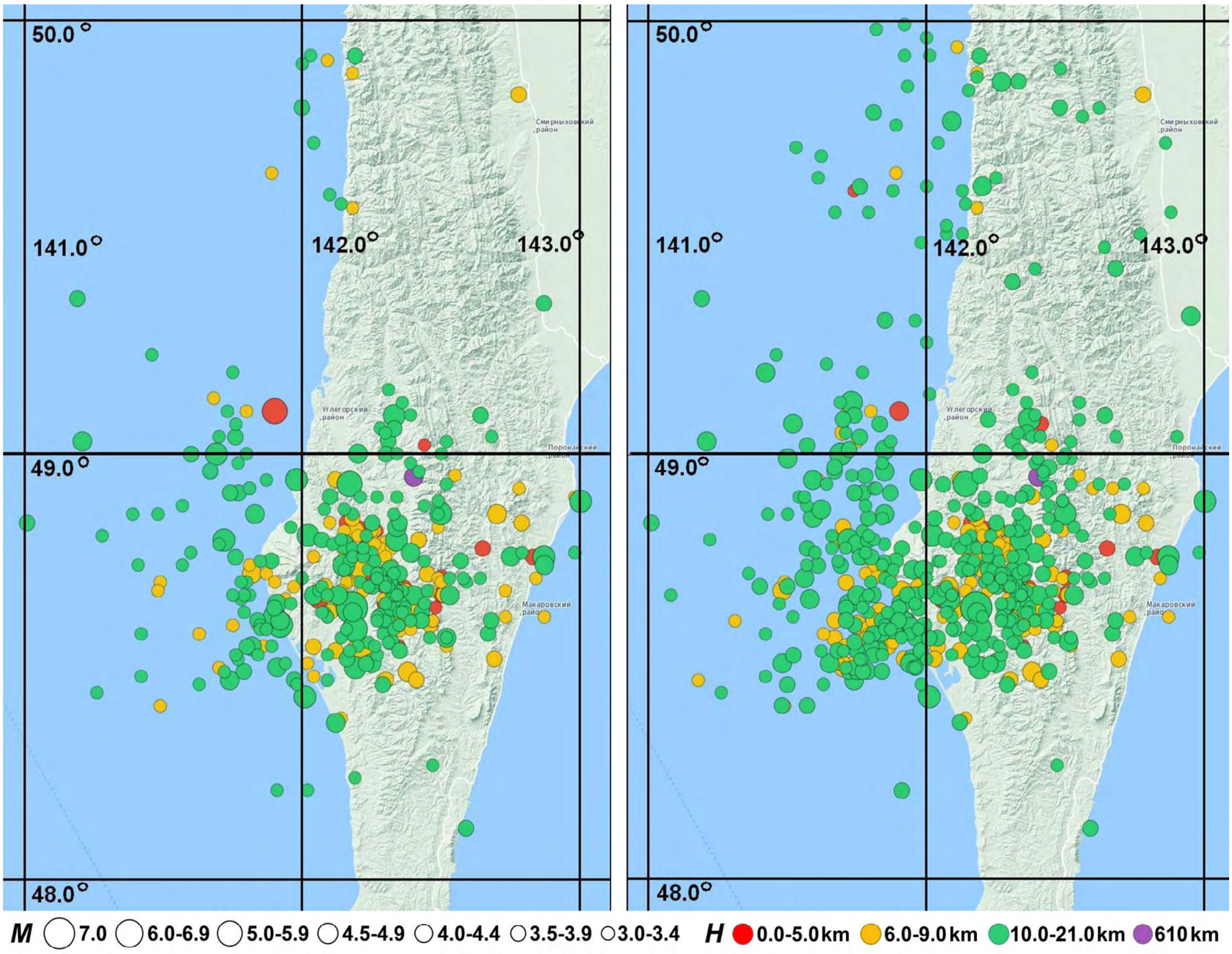

Figure 1. Distribution of the earthquakes epicenters within the estimated area by the data of catalogs no. 1 (left) and no. 2 (right) during the period from 1997 to 2005.

observation period since 1997 with the parameters: hypocenter, magnitude, focal mechanism, as well as macroseismic data. The seismic events with the magnitude M ≥ 3.0 are represented in both catalogs.

The rectangular area with the coordinates from 48.0° to 50.0° N and from 141.0° to 143.0° E has been chosen for study in present work. Earthquakes sampling for computations by each catalog were carried out from 1997 (3 years before the Uglegorsk earthquake) to 2005.

The maps, constructed by the data of the catalogs no. 1 and no. 2, with the epicenters of earthquakes occurred from 1997 to 2005 within the studied area are presented in the figure 1. The sampling by the catalog no. 1 amounts 363 seismic events with M ≥ 3.0, 188 from them are in the range of magnitudes (3.3 ≤ M ≤ 5.0), which are necessary for computations by the LURR method. The sampling by the second catalog amounts 566 earthquakes with M ≥ 3.0, 320 events from them are in the 3.3 ≤ M ≤ 5.0 range.

The spatial and depth distribution of the epicenters of seismic events is presented in the figure 1. Correlation of the data by the catalogs showed an obvious difference in the events number, as well as minor discrepancies in coordinates of the events occurred during the same time period and in the same area. The most part of the earthquakes is located in the depths range of 10–15 km as a whole, except one earthquake with a depth of 610 km, which is presented in both catalogs. Seismic activity is reduced in the depth range from 3 to 10 km by the data of the catalogs.

Comparison of the data from two catalogs points to limitation of the regional catalog of Sakhalin Island earthquakes [Poplavskaya et al., 2006] not only in a quantitative sense, that is conveniently represented on the epicenters maps, but in the assessments of energy values of seismic events, which have been probably made in different magnitude scales. It is very important to verify the estimates through comparison with the results by the sampling from the catalog no. 2 in this situation. Using of the data from catalog no. 1 is undesirable further.

Results

The LURR parameter graphs, constructed using two catalogs for the same estimated area, are identical as a whole, and that is the most important, the anomaly before the Uglegorsk earthquake is noted at the same time in both graphs (fig. 2). It is important also due to significant differences of these catalogs by earthquakes number and epicenters location. Typical increasing of the parameter by several

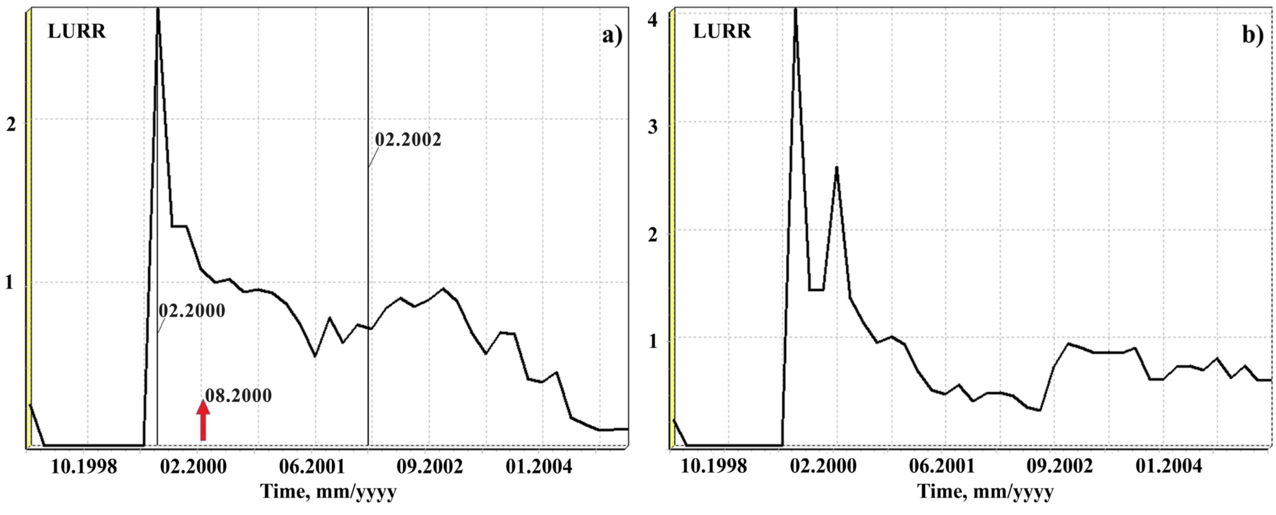

Figure 2. The LURR parameter within the estimated area with the coordinates of 48.0–50.0° N and 141.0–143.0° E during the time period from 1997–2005 by the catalogs no. 1 (a) and no. 2 (b). As an example, in the left graph the moments of alarm beginning (the anomaly) and ending are shown by the lines, and the arrow points to the Uglegorsk earthquake time.

times and its further rapid enough decreasing are observed in the February of 2000, 6 months before the earthquake.

The LURR parameter graph is shown in the figure 3 for the events from 1997 to 2019 by the catalog no. 2. As it can be seen from the graph, for 22 years an additional three significant variations have been noted, which are also defined as the parameter anomalies, besides the anomaly before the Uglegorsk earthquake. These are variations in the April of 2008, in the November of 2014 and in the February of 2019. The last of them points to the alarm period until at least the February of 2021 and may be assessed as an operative prediction. At present, the same assessments are obtained for the territory located southward of the studied area and also in the zone of the Central Sakhalin fault [Zakupin, Boginskaia, 2019]. In the variations of 2008 and 2014 the anomalies before the Uanga and Onor earthquakes, which have been early calculated by the IMGG FEB RAS catalog [Zakupin et al., 2018], can be easily recognized. Our estimated zone (48.0–50.0° N and 141.0–143.0° E) is located 200 km southward of the Uanga earthquake epicenter, but at the same time this anomaly is statistically significant, as well as the anomaly of the Onor earthquake, which epicenter is four times nearer to the estimated zone. We have earlier obtained the sign maximal by a level for the Uanga earthquake almost near its epicenter by the IMGG FEB RAS catalog. But now we have received more clear expression of the sign at a greater distance from the epicenter. The anomaly for the Onor earthquake is comparable to that one, which has been revealed in the previous estimates [Zakupin et al., 2018], but there the estimated zone has been significantly distant from the epicenter of future earthquake.

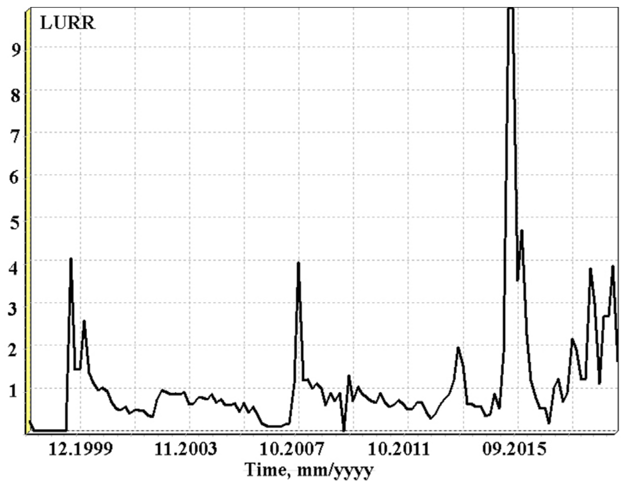

Figure 3. The LURR parameter for the period from 1997 to 2019 by the data of the catalog no. 2 within the estimated area with the coordinates of 48.0°–50.0° N and 141.0°–143.0° E.

Scanning (ellipse-zones searching) was carried out from 48.0° to 52.0° N for verification by the catalog no. 2. It is revealed, that the anomalies reach the maximal values in those ellipses, which centers are close to the epicenters of corresponding earthquakes (fig. 4 a, b). Also note, that the LURR anomaly before the Uglegorsk earthquake slightly increases in the ellipse-zone, which center coincides with the Onor earthquake epicenter (northward of the Uglegorsk earthquake for 1°). However, it completely disappears by further zone shifting towards the north, this can be seen in the zone, which center coincides with the Uanga earthquake. At the same time, the anomaly level before the Onor earthquake practically does not weaken in the zone of the Uanga prediction sign influence (fig. 4 b). In fact, the anomaly of the Uglegorsk earthquake is revealed in the territory bounded with the coordinates of 48.0°–51.0° N and 141.0°–143.0° E.

Let's see if predictive assessments on the Uanga and the Onor earthquakes have changed after alternative computations performing by the catalog no. 2 in comparison with the IMGG FEB RAS catalog. The map with estimated zones is shown in the figure 5 a. The maximal values of the anomalies for these two catalogs and the earthquakes epicenters are marked there. The map demonstrates that the best matching is observed for the catalog no. 2.

The scale is brought to the uniform time (since 2006) to enhance the sensing, and the LURR anomalies are shown in the figure 5 b–e for both events by two catalogs. The anomalies appearance time differs slightly, but the zones space position for the catalog no. 2 comes closer to the earthquakes epicenters. Also note, that the maxi-

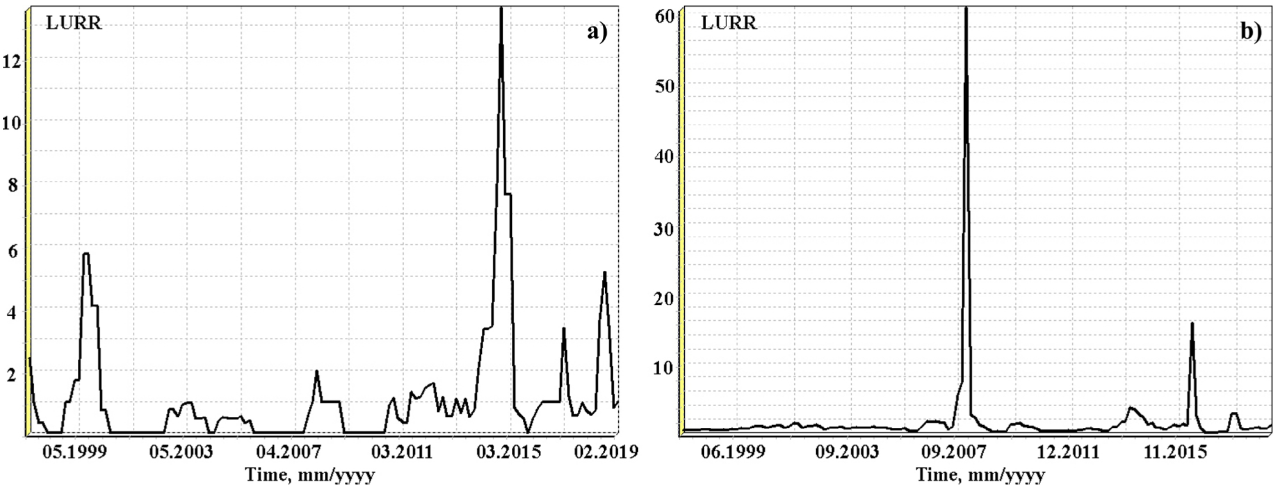

Figure 4. LURR parameter estimates by the catalog no. 2 in the zones, which centers coincide with epicenters of the Onor (a) and the Uglegorsk (b) earthquakes.

mal values of the anomalies increase at a whole (especially for the Uanga earthquake). The anomaly appearance time moved back from the October to the April of 2008 for the Uanga earthquake, but it moved forward from the July to the November of 2015 for the Onor one. The minor oscillations during the anomaly appearance have not disrupted the «Sakhalin» statistics, and the average waiting time still does not exceed two years for all Sakhalin earthquakes. To be sure, the significant quality improvement of the seismic hazard assessments for these two earthquakes by the catalog no. 2 can positively characterize the data quality.

Thus, using the new data (the SB FRC UGS RAS catalog) for the estimates allowed not only to reveal a retrospective precursor of the Uglegorsk earthquake (and also remove the event from the list of missed targets), but to improve the results for near (by the time and position) events, which had been considered earlier.

Let's estimate the LURR method efficiency, after new results have been obtained, by the well-known methodology [Gusev, 1974]. If the prediction is made by the concrete method for one and the same spatial zone and energy range, then the efficiency J may be determined by the following expression:

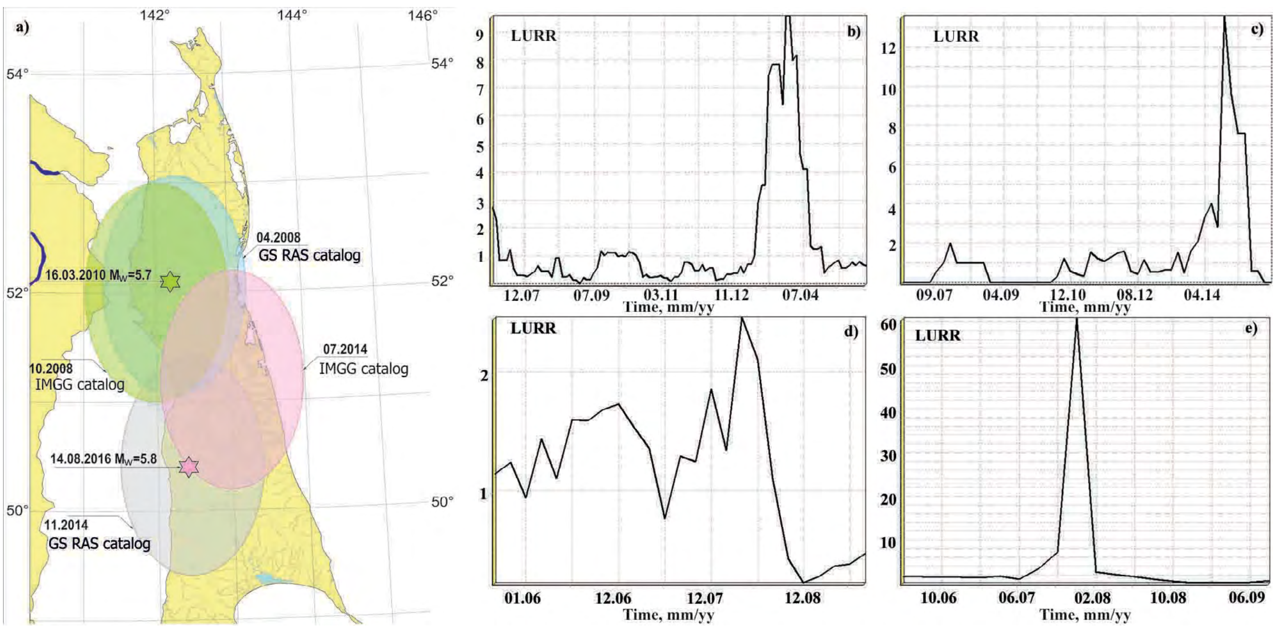

Figure 5. The map with the estimated zones (a), where the LURR anomalies by the IMGG FEB RAS and no.2 catalogs are marked for the Onor (the graphs b and c respectively) and the Uanga (the graphs d and e respectively) earthquakes.

$$J = N_{+} \cdot T/(N \cdot T_{alarm}),$$

where N_{+} – the number of «expected» earthquakes, i.e. the earthquakes conforming to the successful prediction, N – the total number of occurred earthquakes with the parameters (location and energy), that conform to the prediction, T_{alarm} – the common alarm time, i.e. total duration of all predictions, the T – total time of the seismic situation monitoring by the considered method. The efficiency J shows, how many times the number of predicted earthquakes exceeds the number of those, which have got into the common alarm time by accident. It is clear, by accident guessing the efficiency J is equal to 1. So, in our case, when $N = 8$ (if take the Krilyon earthquake with M = 5 into account), there were $N_{+} = 7$ successful predictive assessments (including retrospective). Total observation period amounted 264 mos. (1995–2017), and the alarm time summarized by 7 cases – 93 mos. In the result the J index was equal to 2.48 (contrary to 2.28 before the Uglegorsk earthquake data had been included). This value exceeds the average statistical indexes on the short-terms methods (mainly on the base of geophysical fields anomalies) more than two times [Chebrov et al., 2013].

Conclusion

The results of the LURR parameter estimates by the «Regional catalog of Sakhalin Island earthquakes, 1905–2005» and the SB FRC UGS RAS catalogs pointed to the existence of a zone with the anomaly, which was a precursor of the Uglegorsk earthquake (the August of 2000) in the central part of Sakhalin Island in the February, 2000. Besides, it was shown that «dangerous» zones in a space for the Uanga and Onor earthquakes (their epicenters were a close neighbor of the Uglegorsk estimated zone) were defined by the IMGG FEB RAS catalog (2006–2016 the populating period) with worse accuracy (discrepancy was up to 1°) than by the SB FRC UGS RAS catalog using.

We can add the successful retrospective estimate of the LURR parameter before the Uglegorsk earthquake to the total number of the mid-term assessments of the seismic hazard, carried out by this method for Sakhalin Island. Six such predictive assessments (including the operative prediction for the Onor earthquake in 2016) were made for the earthquakes with a magnitude above 5.5 (the lower limit set by the authors for Sakhalin Island within the LURR method) during last 30 years, while there were seven real events satisfying this condition. Once more successful real time prediction by the LURR method for the Krilyon earthquake (Mw = 5.0) was made in 2017. But it stands out from the common statistics of Sakhalin earthquakes predictions by the fact, that its magnitude is actually less than the expected value.

We believe the results obtained by the LURR method have no analogs among other methods by the efficiency level of received assessments nowadays. The method will be undoubtedly relevant for the mid-term seismic hazard assessments on Sakhalin Island in future. The detailed researches are principally possible in the other seismically active regions, especially as the separate successful assessments have been made earlier in our practice (by New Zealand seismic data [Zakupin, Kamenev, 2017] and Nepal [Zakupin, Jerdeva, 2017]).

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About the Authors

ZAKUPIN Alexander Sergeevich (ORCID 0000-0003-0593-6417), Cand. Sci. (Phys. and Math.), Deputy Director, Leading Researcher of the Laboratory of seismology, Institute of Marine Geology and Geophysics of FEB RAS, Yuzhno-Sakhalinsk, a.zakupin@imgg.ru

BOGINSKAYA Nataliya Vladimirovna (ORCID 0000-0002-3126-5138), Research Officer, Laboratory of seismology, Institute of Marine Geology and Geophysics of FEB RAS, Yuzhno-Sakhalinsk, fily77@mail.ru