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Triggering Factors of Increased Seismic Activity in Priamurye

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Abstract—This study is focused on the annual distribution of seismic activity in Priamurye. An increase in the released seismic energy ($M \geq 3$) was identified in 1970–1975, 1985–1986, 1994–1995, and 2003–2005. It corresponds to the seismic activity peaks reported worldwide. Hence, it can be suggested that a global process, such as variations in the planet rotation velocity, is involved in the initiation of relatively strong earthquakes under the Priamurye intraplate conditions. The seismic energy release is maximum during the time intervals when the frequency value and, accordingly, the rotation velocity are minimum or maximum. Hence, this process can be considered as an important factor for triggering an increase in regional seismicity. The energy distribution of weak earthquakes in terms of years ($M < 3$), except for seismicity peaks characteristic of relatively strong events, shows an increase in seismicity in 1980–1983, 1990, 1998, 2000–2001, and 2007. It corresponds to the periods of increased seismic activity of deep-focus earthquakes in the Pacific subduction zone. This fact makes it possible to consider the seismic activity in the Pacific subduction zone as an important factor for triggering weak earthquakes in Priamurye.

Keywords: intraplate seismicity, seismic energy, planet rotation velocity, and Priamurye

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INTRODUCTION

The seismic process is characterized by a number of features, one of which is its irregularity. Both seismic activation and quiescence periods are observed in seismically active areas of different levels. The seismic activity is assessed based on the total seismic energy or the number of earthquakes occurred over a certain period of time. The issues of earthquake prediction and seismic hazard assessment in the Priamurye (Amur region) intraplate conditions require an understanding of the physical processes which control an increase in seismicity. A number of researchers argue that the seismic activity level in the intraplate areas depends on tectonic stresses transmitted from plate boundaries of different types [1, 10]. Based on a numerical experiment, the intracontinental mid-focus earthquakes occur in response to an increase in viscous stresses inside oceanic plates sinking down into the mantle [11]. Seismicity was found to be related to the disturbance transmission from mid-ocean ridges within intraplate areas of the North American and Eurasian plates [24]. An increase in seismic activity can coincide with changes in global sea level, which is an indicator actively responding to various factors, including geological and geophysical processes caused by the sinking of lithospheric plates into the mantle at subduction zones [31, 32].

However, a number of papers demonstrated a different approach to explaining non-uniform distributions of seismicity. The seismic activity increased simultaneously in the areas located at a considerable distance from each other makes it possible to suggest an involvement of the global process in the seismic activation. Nonuniform rotation of the Earth is an example of such a global process [3, 27, 36–38; 46].

The correlation of seismic activity maxima with rotation irregularity was determined in time intervals of different duration for the whole world or its individual regions located in different geodynamic settings [15, 16, 18, 30, 42, 44, 47]. The influence of rotation velocity variations on the lithosphere, its deformation fields, and the stress–strain redistribution has been studied to date [23]. The nonuniform planet rotation can act as a trigger for strong earthquakes or be an energy source of increased seismicity [33, 35, 40]. Three global components were identified based on a detailed analysis of the seismic process. The global component (T) is caused by a physical mechanism common to the entire planet, with a characteristic variation time of 10–15 years. The more local component (M) causes variable stress at plate boundaries with a period of 3 years. The regional component (R) records a long-term decline or increase in seismicity lasting for about 25 years [3, 4, 39].

The periods of increased seismic activity in Priamurye are studied in this paper. Most of this region is located in the intraplate conditions (northeastern margin of the Amur Plate) characterized by a moderate seismicity (Figs. 1a, 1b). To identify the dynamic factors contributing to seismic activation, we compared the seismicity peaks with the low-frequency component of the planet's rotation velocity and the deep-focus seismicity of closely located segments of the Pacific Plate subduction zone (Fig. 1b). The earlier studies of seismic activity in two phases of changes in the Earth's rotation velocity (extension–compression) did not reveal statistically significant deviations in the number of earthquakes [29].

RESEARCH DATA AND METHODS

Seismicity in Priamurye was analyzed using the catalog of the Kosygin Institute of Tectonics and Geophysics, Far East Branch, Russian Academy of Sciences, containing the data on earthquakes from the published composite books *Earthquakes in the USSR*, *Earthquakes in Russia*, and *Earthquakes in Northern Eurasia* [7–9]. The representativeness of earthquake catalogs repeatedly changed due to variations in the number and configuration of seismic stations in the region. In 1961–1966, earthquakes with $M = 3.8$–4.2 were representative only in the northwest of Priamurye, whereas in the 1970s, such earthquakes were representative for the whole area. Then, due to an increase in the number of seismic stations in the period from 1990 to 2015, earthquakes with $M = 2.0$–2.5 became representative for almost the entire region [28].

Seismic energy was chosen as the main parameter to determine the seismic activity level in the region or its individual parts, but the number of earthquakes was also used in some cases. Seismic energy values were summed up in terms of years using the formula: $\text{Lg}E = 4.8 + 1.5\ \text{M}$, where E was a seismic energy (J), and M was a magnitude. Due to the fact that the study area is characterized by a moderate seismicity (seismic events with a magnitude of 4 or more are few, and with a magnitude of 5 are rare), magnitude 3 was chosen as the threshold separating relatively strong earthquakes from weak events. The released seismic energy calculated using relatively strong seismic earthquakes with $M \geq 3$ and the number of earthquakes with $M \geq 4.5$ in annual intervals in 1960–2015 demonstrates consistent results. This means that the seismic activity maxima identified in the region are unambiguous (Figs. 2a, 2b). In order to unambiguously identify time intervals of increased seismicity at different hierarchical levels, the seismic energy was studied in terms of years both in the entire region and its four separate equidimensional areas and zones subjected to earthquakes.

The ISC international catalog (Bulletin of the International Seismological Center) [41] was used to study the seismic activity of Pacific subduction segments. We calculated the number of earthquakes and seismic energy for earthquakes with $M \geq 4$ and a focus depth of more than 300 km in the Sakhalin–Kuril segment of the Pacific subduction zone located near Priamurye. This paper also provides the number of seismic events in the larger Japan–Kuril segment of the Pacific subduction zone.

RESULTS

The highest seismic activity in Priamurye (48–56°N; 126–140°E) was observed in 1986. An increase in seismic energy released by weaker earthquakes was noted in 1972, 1994, 1975, and 1998, while peaks of even lower intensity occurred in 1970, 1975, 2003, and 2007. (Figs. 2a, 2b).

Based on the analysis of seismic activity in 1983–1987, a range of earthquakes occurred in China in this period near the border with Russia, and some of them reached a magnitude of 5 or more. Therefore, we calculated the seismic energy excluding these clusters of seismic events, i.e., the area with coordinates 48–56°N, 128–140°E in the same time range. Within these boundaries, the seismic energy maximum was noted in 1994. In addition, a relatively intensive release of seismic energy occurred in 1984–1985 (Fig. 2c). Less significant peaks were observed in 1970, 1975, 1999, 2003, and 2006.

In terms of seismic energy distribution of weak earthquakes with $M < 3$, except for those close to activity peaks, including relatively strong events in 1985, 1994, and 2003, the intensive seismicity maxima were distinguished in 1980–1982, 1990, and 2000–2001, 2007 (Fig. 2d).

Based on the analysis of seismic activity in four areas of the study region, the seismicity increases approximately in the same time intervals as the seismic activity peaks described above (Fig. 2). In area I, an increase in seismicity was noted in 1972, 1975, 1985, 1994, 1999, 2004, and 2008. Area II is characterized by intensive maxima in 1985 and 1994. In area III, the seismicity increased in 1970, 1994, and 2007. In area IV, where anomalous seismic activity was detected in 1985–1986, near the border between Russia and China, we calculated the seismic energy without clusters of earthquakes occurred at this time, i.e., in the region with coordinates 48–50°N, 129–133°E. It is seen that the intensive maximum in 1994 was accompanied by less significant peaks in 1990 and 1997. It should be noted that the seismic activity after 2000 was characterized by greater variability in the study areas. The most significant peaks in terms of intensity were observed in 2005 (area I–IV) and in 2007 (area III). Weaker peaks occurred in 2003, 2004, and 2008 (Fig. 3).

In the local clusters of earthquake sources, the seismicity mostly increased in 1985–1986, 1994–1995, and 2003–2005 (Fig. 4). In addition, some zones were characterized by higher seismicity in 1972–1974 and 1997–1998. Zones 5 and 7 were characterized by anomalous release of seismic energy in 2007.

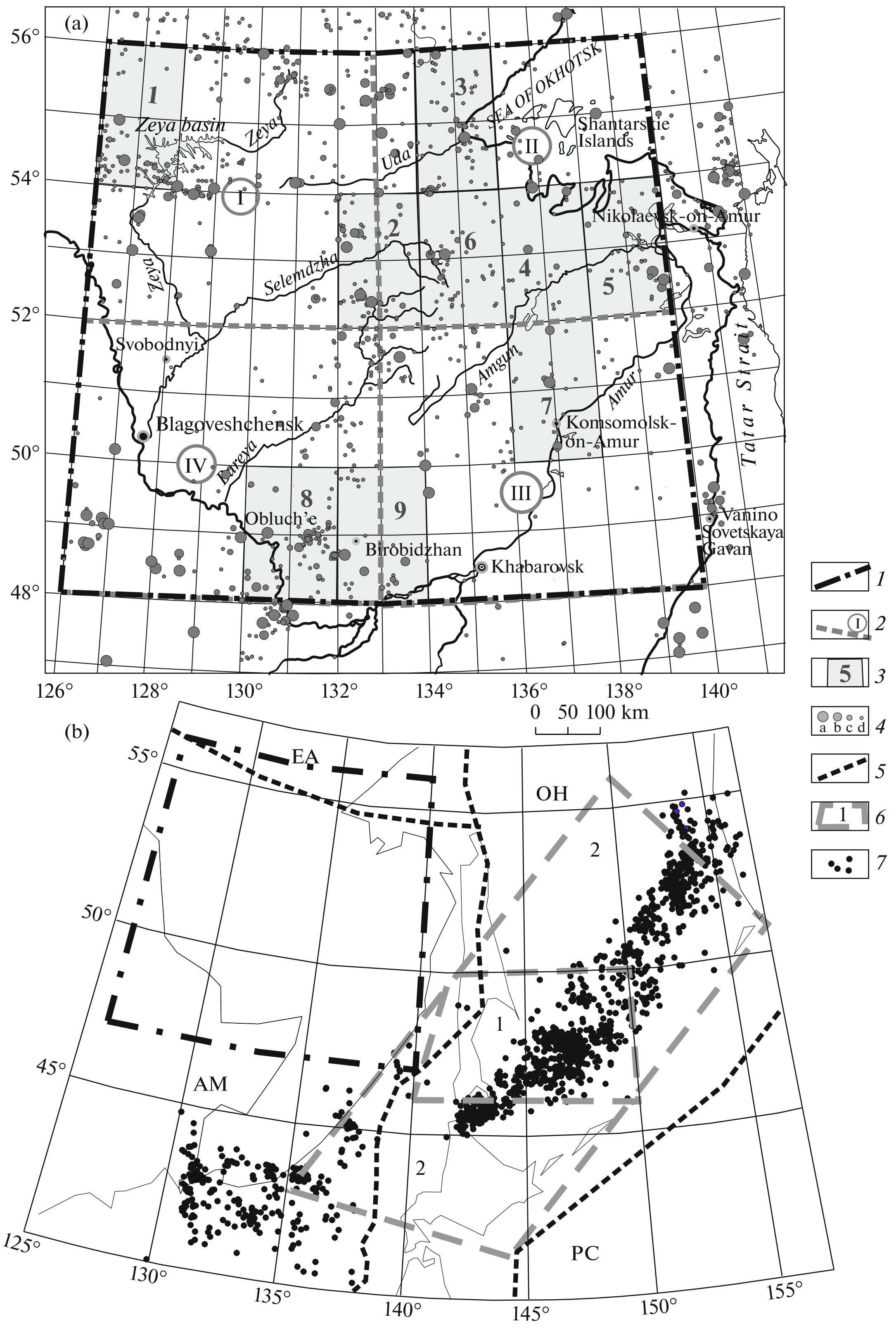

Fig. 1. The seismic activity of (a) the research area and (b) its tectonic position. (*1*) Boundaries of the research area; (*2*) boundaries of areas and their number; (*3*) boundaries of earthquake clusters; (*4*) earthquakes: (a) $M \geq 5$; (b) $5 > M \geq 4.5$; (c) $4.5 > M \geq 4.0$; (d) $4.0 > M \geq 3.0$; (*5*) plate boundaries: (EA) Eurasian, (AM) Amur; (OH) Okhotsk, (PC) Pacific; (*6*) Pacific subduction zone segments: (1) Sakhalin–Kuril, (2) Japan–Kuril; (*7*) deep-focus earthquakes ($H \geq 300$ km, $M \geq 4.0$).

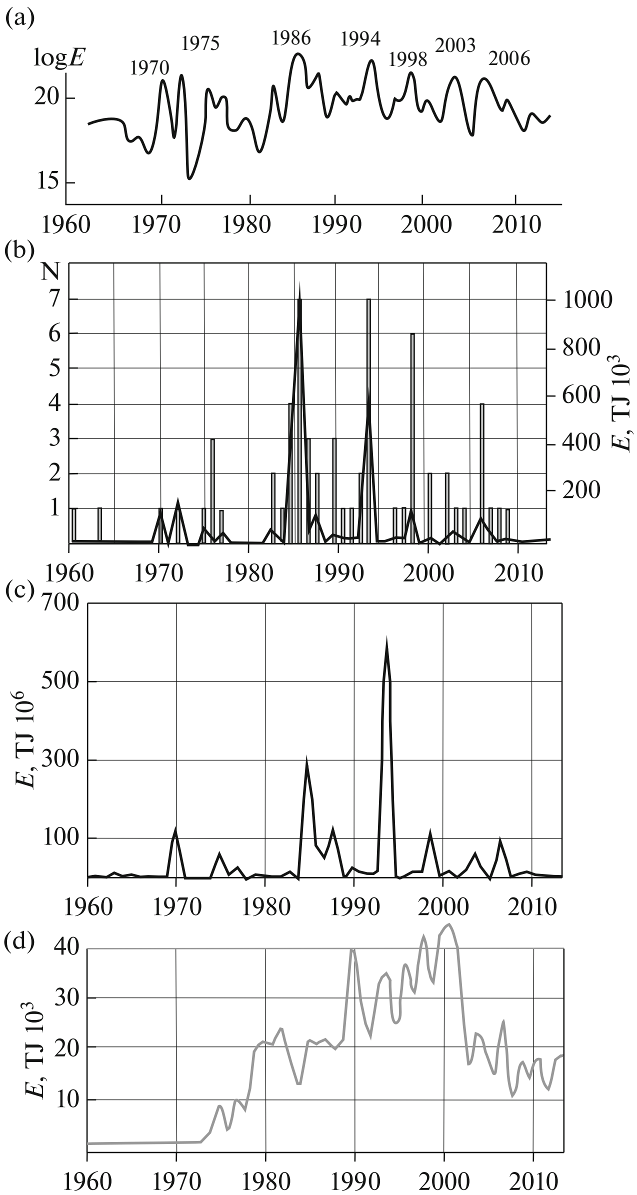

Fig. 2. The seismic energy distribution in terms of years in Priamurye (1960–2015). (a) Annual distribution of released seismic energy on a logarithmic scale; (b) ratio of the total seismic energy of relatively strong earthquakes ($M \geq 3$) to the number of earthquakes ($M \geq 4.5$) in terms of years; (c) seismic energy distribution in the region with coordinates (48–56° N; 128–140° E); (d) annual distribution of seismic energy of weak earthquakes ($M < 3$).

DISCUSSION

Based on the analysis of the annual seismic activity distribution throughout Priamurye, individual regions and zones with clusters of earthquake sources, the seismic energy of relatively strong earthquakes with $M \geq 3$ mostly increased in 1970, 1972, 1975, 1985–1986, 1993–1995, and 2003–2005, while a lower-intensity peak was observed in 1997–1999 (Figs. 2, 3, 4). In general terms, the described intervals of increased seismic activity correspond to a summary of the annual number of events and the seismic energy distribution in the Priamurye and Primorye regions, where the seismicity also increased in 1985–1986, 1994, and 2003 [28]. At that time, higher seismic activity was also observed in other adjacent seismically active areas. Similar seismicity peaks were identified in the Kuril–Kamchatka zone with the highest variations in amplitude of seismic energy in 1975, 1982–1987, and 1993–1996 [26, 34]. Some described seismicity peaks were found in the Asian active regions such as the Baikal Rift Zone or in the Himalayas in different magnitude ranges [12, 16, 25]. The seismic energy enhancement peaks identified in Priamurye corresponded to the higher-seismicity periods recorded worldwide [13, 17, 39] (Figs. 5a, 5b). The number of annually recorded earthquakes and the number of earthquakes with $M \geq 4$ are indicative of a slight increase in seismicity in 1975, as well as more significant seismicity peaks in 1985–1986, 1993–1995, and 2005 [13, 39]. An anomalous increase in the seismic moment magnitude was recorded in 1994–1995 and 2005 [17].

In the described time intervals, strong earthquakes occurred in the world: in 1985–1986, three events with $M \geq 8$; in 1994–1996, four events; and in 2004–2005, six events, the strongest earthquake (Sumatra, December 26, 2004; M = 9.1–9.3) [43]. In 1973–1974, 1983–1986, and 1994–1995, an increase in seismicity in Asia was accompanied by a range of unique seismic events. In the Hindu Kush, with the maximum seismicity in 1974, the periodic time course of the aseismic band was interrupted in 1973 due to variations in the planet's acceleration sign [19, 20]. In the period of 1983–1985, deep-focus earthquakes on December 30, 1983 (M = 7.8; h = 210 km) and July 29, 1985 (M = 7.0; h = 70 km) were accompanied by aftershocks with $M > 4.5$ not observed in the region for the entire period of instrumental observations. These unique earthquakes were characterized by rising source of the 1985 event to the minimum depth of the upper mantle and by the breakthrough, i.e., filling by epicenters of repeated shocks of the aseismic band periodically changed in the depth range of 120–180 km with a cycle of 10–11 years [21]. In 1992–1993, the seismotectonic activation in the Baikal rift zone was also accompanied by unique seismic events. At that time, earthquakes recorded the tectonic stress restructuring. The course of these events is indicative of the predominant near-horizontal compression with a reverse fault component of slips, whereas the regional earthquakes are generally characterized by typical rift processes with fault-type slips [5]. The global nature of strong seismogeodynamic activation in 1993–1994 was also confirmed by other works [31]. In the seismically active regions, adjacent to Priamurye (Kuril Islands and Sakhalin Island), two strong earthquakes occurred during this period of time: Shikotan on October 4, 1994, Mw = 8.3 and Neftegorsk on May 28, 1995, Mw = 7.6.

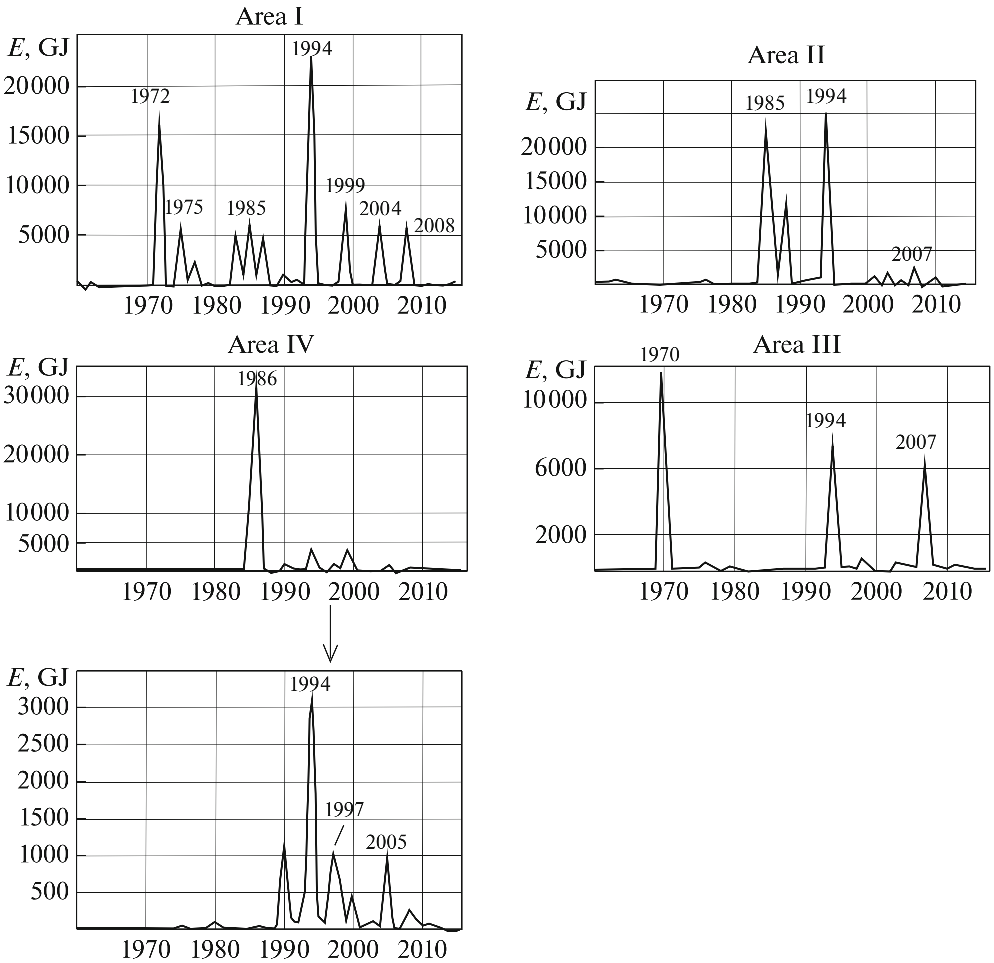

Fig. 3. The seismic energy in certain Priamurye areas in terms of years.

In 1985–1986 and 1994, seismic activity peaks coincided with the occurrence of higher amplitude tectonomagnetic anomalies recorded in the central part of the Baikal rift zone (Fig. 5c). Magnetic anomalies of this type are caused by an increase in piezomagnetic properties of the Earth's crust rock under variations in tectonic stresses or their regional redistribution [2, 5]. In this case, the magnetic anomaly of 1994 was much higher than that of 1986. Correspondence of the seismic activity peaks in Primorye to the maximum number of seismic events in the world, an increase in seismicity in the same time intervals in other seismically active regions, as well as consistency of the seismic activity peaks with the tectonomagnetic anomalies obtained near the Baikal rift zone, make it possible to suggest that a global process is involved in increasing the seismic activity. This process caused substantial changes in the stress–strain state of a large area, accompanied by seismic movements along the faults (Fig. 5c). The nonuniform planet rotation can be such global process (Fig. 5d). It was proved earlier that the correlation coefficient between the modulus of the time derivative from the Earth's daily rotation velocity, which characterizes the acceleration and deceleration of the Earth's rotation, and the annual number of relatively strong earthquakes reaches high values [4].

Based on the analysis of the seismic energy released in the period of 1960–2015 in Priamurye, the seismic energy maxima correspond to the intervals where frequency values and, accordingly, rotation velocities are minimum or maximum. A minimum rotation velocity of 1971–1975 is marked by slight seismic activity bursts in 1972–1975, while higher frequency values of 1984–1986, by seismic energy bursts in 1985–1986. The regional seismic activations with a maximum in 1994 correspond to the following period of reduced rotation velocity in 1992–1994. A frequency increased in 2003–2005 corresponds to the seismic energy peaks in 2003 and 2005 (Fig. 5d).

Hence, based on the given data, it follows that the nonuniform rotation of the Earth is an important triggering factor accompanied by high neotectonic stresses which initiate earthquakes with a relatively high magnitude ($M \geq 3$) in the Priamurye intraplate

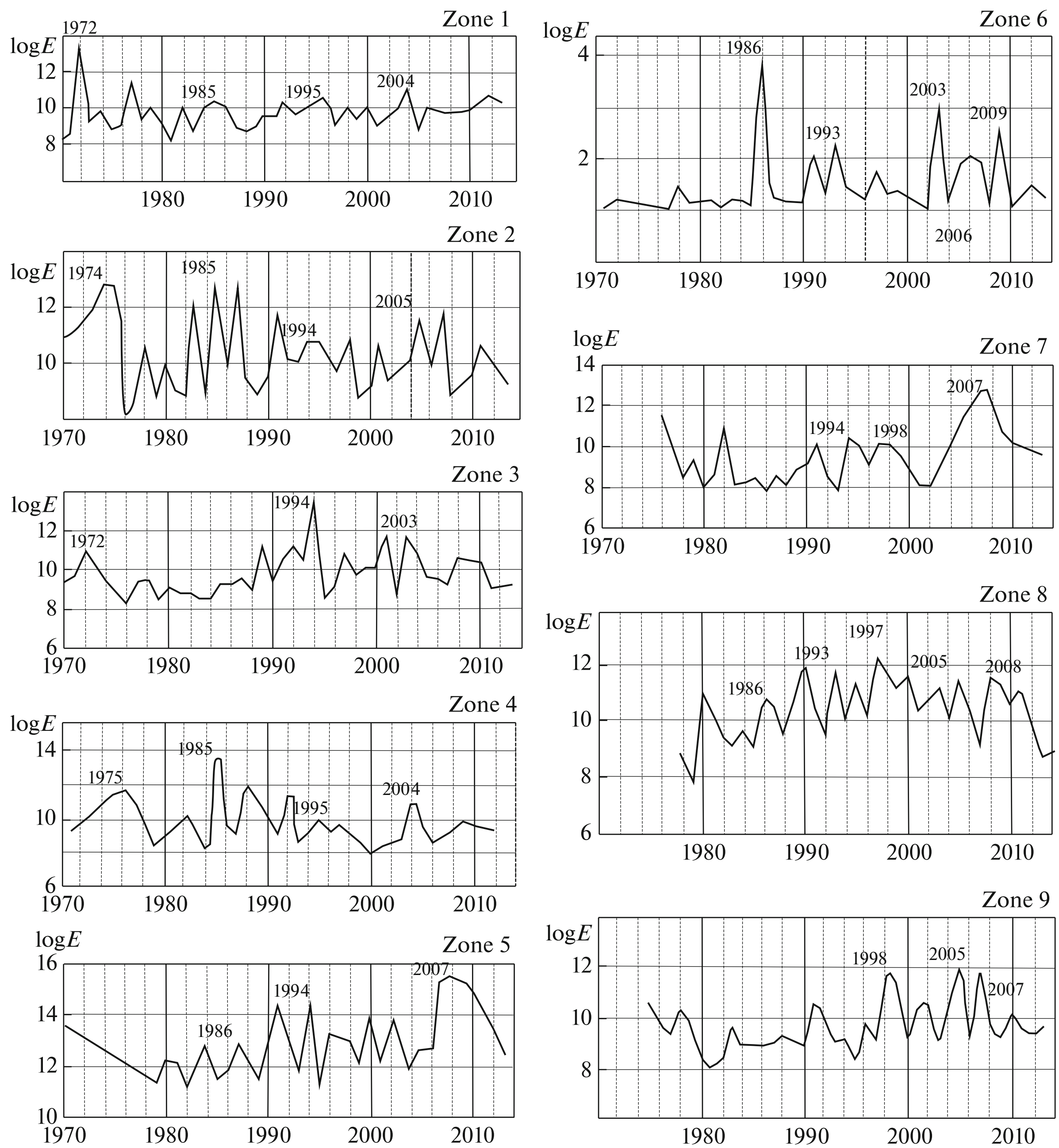

Fig. 4. The logarithm of the seismic energy in the Primorye earthquake clusters.

conditions. This pattern likely confirms a common component for all regions of the world in the seismic process with the characteristic time scale of 10–15 years (the T-component) [3]. In this case, seismic event triggering is possible only in the prepared areas of the Earth's crust. Based on the analysis of the seismic activity in four areas of the study region, only area I is marked by all four of the above-described intervals of increased seismic activity. In other words, this area has zones prepared to all points of the variations in the planet's rotation velocity (frequency) sign in this time interval (Fig. 3). According to this fact, area I is likely the most seismically active in the region. In other areas, only two or three points of variations in the rotation frequency sign are marked by the higher seismicity. Similar to these areas, in the cluster zones, seismic activity peaks correspond both to all points of variations in the planet's rotation velocity sign and only to two or three of them (Fig. 4).

As follows from the seismic energy distribution of weak earthquakes ($M < 3$), the increased seismic activity, in addition to the above-mentioned seismicity peaks typical for fairly strong earthquakes, was noted in 1980–1983, 1990, 1998, 2000–2003, 2005, and 2007. The seismic energy outburst in 2000–2003 was followed by a drastic decrease in the number of weak earthquakes (Fig. 6a).

Based on the analysis of seismic energy of weak events in Priamurye and seismic activity of deep-focus earthquakes in the Sakhalin–Kuril segment of the Pacific subduction zone, the weak seismicity intensifications in Priamurye in 1980, 1990, 2000, and 2007 corresponds to the peaks of an increased number of deep-focus seismic events in this segment of the Pacific subduction zone located close to the study region (Figs. 6a, 6b). Variations in the seismic activity of weak earthquakes in Priamurye are likely due to fluctuations in the Pacific Plate motion followed by seismic movements. The fluctuating deformations and movements at the plate boundaries with a period of 2–3 years or 5–6 years are described in a number of works [4, 21, 39].

The annual distribution of seismic energy of weak earthquakes in Priamurye also shows seismicity peaks characteristic of relatively strong earthquakes (1975, 1985–1986, 1994–1995, and 2004). However, in terms of the number of deep-focus earthquakes in the Sakhalin–Kuril segment, the seismicity increases in 1985, 1996–1997, and 2004 only (Fig. 6b). The above-described increase in seismicity is best manifested in the larger subduction area of the Pacific Plate (Japan–Kuril segment) in the number of deep-focus earthquakes (Fig. 6c). Variations in the planet's rotation velocity likely have a triggering effect causing increased seismicity also only in prepared segments of the large seismically active areas such as the Pacific subduction zone. The correlation coefficient of the seismic energy of weak seismicity in the Priamurye and the number of deep-focus earthquakes in the Japan–Kuril subduction segment is $r = 0.57$.

The long-term component (25 years or more) is not distinguished in the seismicity of relatively strong earthquakes in Priamurye, but the seismic activity of weak earthquakes is marked by a long-term increase until 2000–2002, consistent with an increase in the number of deep-focus earthquakes in the Japan–Kuril subduction segment (Figs. 6b, 6c). A sharp decrease in the number of earthquakes was recorded in the Sakhalin–Kuril segment in 2002, while in the Japan–Kuril subduction zone segment, in 2004 (Figs. 6b, 6c). Earlier, drastic changes in the subduction zone were revealed in the global seismic noise trends in mid-2003, defined as a break point. After 2003, the trends corresponded to those in the areas of enhanced seismic hazard [18, 42].

It should be noted that in addition to the four time intervals of increased seismicity described above, corresponding to the points of variations in the planet's rotation velocity sign, the seismicity increase in 1997–1999 is noted in the distribution of the number of relatively strong earthquakes ($M \geq 4.5$), as well as in the graphs of the seismic energy of individual areas I and IV and zones 7–9 (Figs. 2–4). Such an increase can be caused by some processes in the Pacific subduction zone: the seismicity peak of deep-focus earthquakes in the Sakhalin–Kuril segment was in 1997 (Fig. 6b).

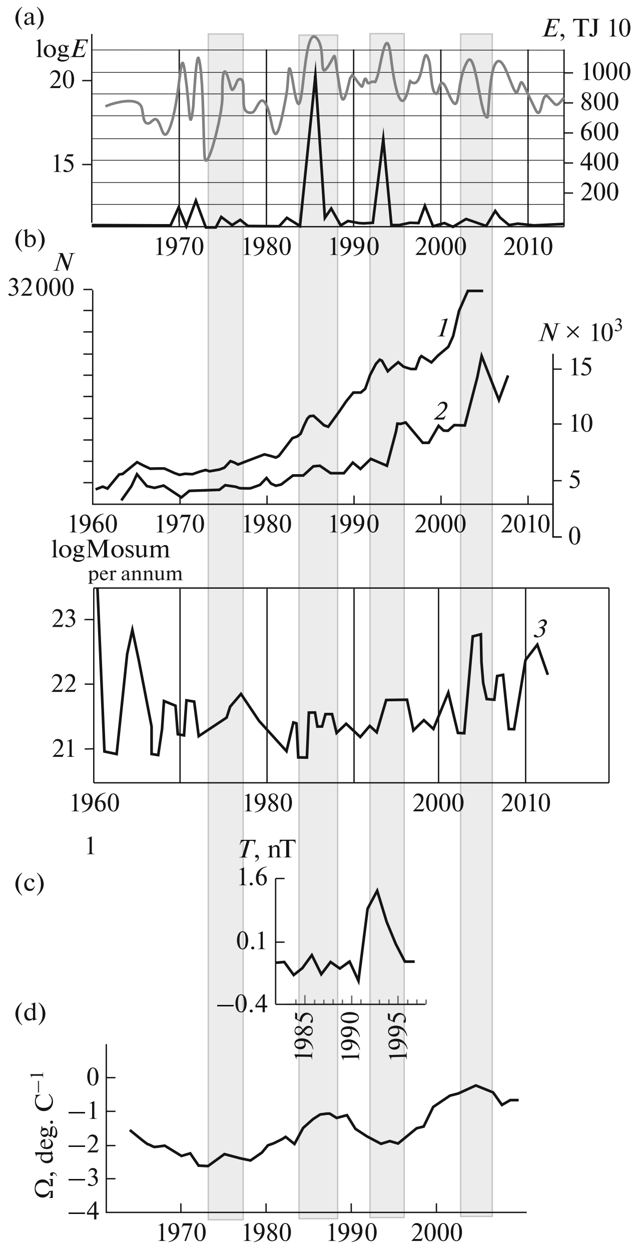

Fig. 5. Correspondence of the seismic energy peaks in Primorye to the reports on seismicity around the world. (a) Annual distribution of seismic energy in Primorye (upper graph is seismic energy logarithm; lower graph, released seismic energy, TJ); (b) global seismic activity: (*1*) the number of annually recorded earthquakes in the global catalog, according to [13]; (*2*) variations in the global seismic activity of earthquakes ($M \geq 4$) in 1964–2008, according to [39]; (*3*) global course of seismic moment release in the depth range of 0–100 km, according to [17]; (c) tectonomagnetic anomalies, according to [6]; (d) averaged variations in rotation frequency, according to [39].

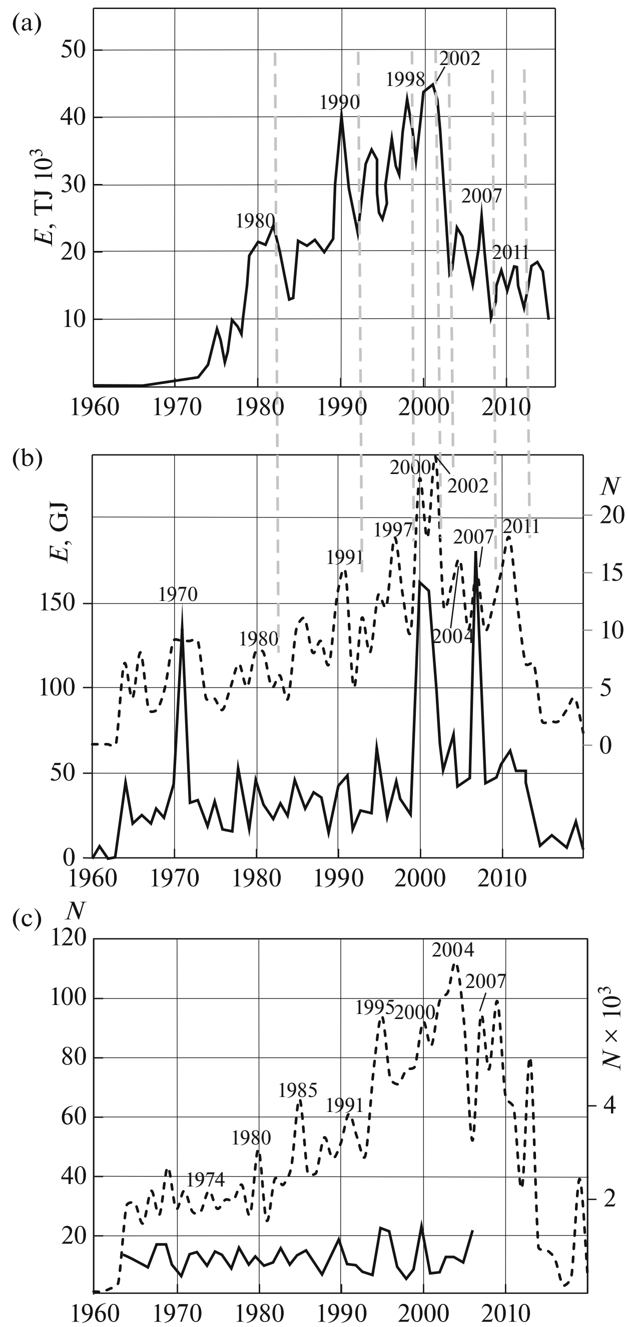

Fig. 6. Correspondence of the seismic energy of weak earthquakes ($M < 3$) in Priamurye to the seismic activity of deep-focus earthquakes in the Pacific subduction zone. (a) Annual energy distribution of weak earthquakes in Priamurye; (b) the number and seismic energy of deep-focus earthquakes ($H > 300$ km, $M > 6$) in the Sakhalin–Kuril segment of the Pacific subduction (dotted line shows the number of earthquakes; seismic energy is indicated with black); (c) number of deep-focus events ($H > 300$ km, $M > 6$) in the Japan–Kuril segment (shown with a dotted line) and the northern branch of the Pacific subduction (black), according to [39].

Other global processes could also be involved in the seismicity intensification, because the seismic activity was observed at that time in some parts of Asian regions [14, 16, 22, 45].

In addition, area III and cluster zones (5, 7, and 9) are characterized by an increase in seismic activity in 2006–2007, which does not occur at the point of variations in rotation velocity. An additional issue is the separate manifestation of 2004 and 2007 peaks in the Pacific subduction zone in 2004 and 2007 (Fig. 6) and in 2005 and 2007 in zones 8 and 9 (Fig. 4). The seismicity increase at this time corresponds to the seismic activity peak in the Sakhalin–Kuril segment of the Pacific subduction zone (Fig. 6b). It is likely that area III is under a relatively strong influence of processes in the Pacific subduction zone at certain time intervals.

CONCLUSIONS

(1) Based on the study results, the Priamurye region has been characterized by the correlation of periods with amplification of the released seismic energy of relatively strong earthquakes ($M \geq 3$) with time intervals of reduced or increased planet's rotation frequency (velocity) in the period of 1970–2015. In other words, variations in the planet's rotation velocity act as a trigger for most relatively strong earthquakes in the Priamurye intraplate conditions.

(2) The seismicity intensification periods in four regions correspond to all intervals of variations in the planet's rotation velocity in one case. In other areas, seismic energy increases in two or three of four points of variations in the Earth's rotation frequency (velocity) during the study period.

(3) No significant seismic activation was revealed in individual areas and zones, except for the time of variations in the planet rotation frequency. The increased seismicity in some areas in 1997–1999 needs further studies.

(4) The maximum annual distribution of the total energy of weak seismic events ($M < 3$) in Priamurye corresponds to the higher-seismicity peaks (seismic energy and the number of deep-focus earthquakes in the Sakhalin–Kuril segment of the Pacific subduction zone). Hence, it can be stated that weak seismic events are triggered by variable stress at the plate boundaries.

CONFLICT OF INTEREST

The author declares that she has no conflicts of interest.

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