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GEOPHYSICS

High Q-Factor Extrema of Seismicity Spectra in Different Regions of the World

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In this paper, we demonstrate high Q-factor extrema of seismicity spectra at periods of 24, 12, and 8 h, revealed by the Fourier analysis of earthquake catalogs in different regions of the world. This effect is mainly manifested for weak earthquakes and becomes insignificant with the increase of the earthquake energy. The diurnal periodicity usually has a maximum during night time, but this phenomenon is absent in some regions. Periods of 12 and 8 h are usually independent harmonics. Increases in the spectral components at periods of lunar–solar tide other than 24 and 12 h were not found.

The existence of diurnal periodicity of earthquakes was already known in ancient Greece. More than two thousand years ago, Aristotle noted in a discussion on the nature of earthquakes that “the nighttime shocks are more frequent and stronger, whereas the daytime shocks happen only at noon” [1, p. 501]. However, the causes of diurnal periodicity are still unknown. Scholars still doubt the reality of the existence of such periodicity [2] or consider it a human-related phenomenon [3].

Figure 1 shows a comparison of the diurnal evolution of seismicity calculated from the earthquakes at the Garm test area (GTA) [4] and the plot based on processing of the US National Oceanic and Atmospheric Administration (NOAA) data. One can see a good correlation both in phase and in amplitude. This can be related to the common nature of the phenomenon in different regions of the world. In our study of the diurnal periodicity of earthquakes, we made an attempt to collect and analyze earthquake catalogs in a maximum number of regions around the world.

Active correspondence with foreign colleagues and intensive Internet searches, as well as analysis of our data and the data of our seismologist colleagues, allowed us to analyze approximately 20 earthquake catalogs from different regions of the Earth, which sometimes partly overlap. In this work, we mainly analyzed the earthquake catalogs from 12 regions (table). We give only brief information about other regions.

The spectra were calculated using the classic Fourier method. The signal consisted of delta functions with moments of the time of the events. The calculations were performed only for short periods (from 1 h to 2 days). We also determined the components for different periods of the lunar–solar tide [6]. The shape of the periodic component was calculated using the method of superposition of epochs [7] (hereafter, the superposition method) by summation over the entire catalog in half-hour intervals within time windows equal to the period studied in the work.

If the periodic signal has a steplike rather than sinusoidal shape, the main period in its spectrum will be

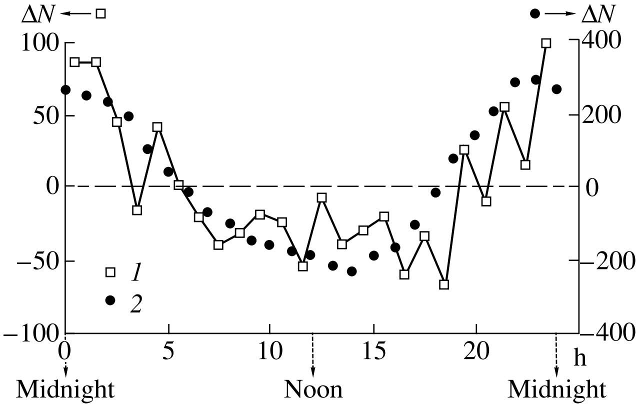

Fig. 1. Deviation of the number of earthquakes (summed within a day using the superposition method over the entire observation period) from their hourly mean values. (*1*) NOAA catalog [5]; (*2*) catalog of earthquakes in the Garm test area. Time is local. Hourly intervals for the first catalog correspond to exact values from the middle of the first hour to the middle of the next hour (for example, 23:30–00:30, … 22:30–23:30). Hourly intervals for the second catalog correspond to the values from the beginning of the hour to its end (for example, 23:00–00:00), …, 22:00–23:00).

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Characteristics of earthquake catalogs

Region	Time interval	Daily number of events	$M_{\min}/M_{\text{rep}}$	Total number of events	Coordinates	Gravity center of epicenters	Data source
Garm test area	1955–1989	6.81	0.9/1.4	87089	37°–41°N 69°–72°E	38.90°N 70.58°E	Schmidt Joint Institute of Physics of the Earth, RAS (OIFZ)
California, south	1990–2004	11	0.6/1.4	57328	31°–37°N 116°–126°W	34.72°N 117.24°W	US Geological Survey
Nevada	2000–2004	17.22	1.0/1.2	29471	35°–41°N 114°–121°W	37.70°N 117.90°W	University of Nevada, Reno
Canada, Quebec	1996–2004	8	0.3/1.5	44445	45°–60°N 60°–80°W	47.52°N 70.76°W	Geological Survey of Canada
Kazakhstan	1980–2004	2	1.7/2.0	19577	39°–49°N 68°–86°E	42.07°N 77.44°E	Institute of Seismology, Republic of Kazakhstan
Central Asia	1970–1990	0.49	1.0/2.1	3842	39°–44°N 69°–76°E	41.51°N 72.70°E	OIFZ
Caucasus	1960–1990	3	1.0/2.0	40925	36°–46°N 37°–53°E	41.06°N 45.46°E	Institute of Geophysics, Georgian SSR
Mediterranean Sea	1999–2004	1.3	1/2.5	2850	36°–45°N 10°–32°E	42.12°N 16.84°E	European Mediterranean Seismological Centre
Fennoscandia	1999–2004	0.9455	0.1/1.3	1805	58°–70°N 2°–24°E	61.50°N 17.05°E	NOPCAP
Iceland	1995–1999	164.38	0/2.3	300000	61°–67°N 15°–24°W	64.49°N 20.46°W	Iceland Meteorological Office
North Sea	1994–2004	1.169	0.2/1.3	5977	55°–65°N 0°–15°E	56.43°N 5.99°E	University of Bergen, Norway
Spain	1980–2004	2.31	0.8/3.8	21142	20°–46°N 10°E–20°W	37.93°N 3.63°W	National Geographical Institute, Spain

Note: $M_{\min}/M_{\text{rep}}$ are minimal and representative earthquake magnitude, respectively. Names of the regions are conventional; sometimes they reflect the source of the data rather than the geographical location of the region, because in some cases the regions overlap significantly, in particular, California and Nevada, Fennoscandia and the North Sea, and Central Asia and Kazakhstan. The Garm test area is a special case of a local and dense network of observations. Actually, Quebec is given under the name of Canada.

supplemented with periods equal to T/n, where n is a whole number. This means that divisible periods could result from the fact that the shape of the signal differs from the harmonic one; i.e., they would lack independent sense. The application of the superposition method for all divisible periods with the analysis of the shape and signal amplitude allowed us to find out whether the observed divisible signal is independent. Tests of the applied algorithms and programs using random earthquake catalogs showed the absence of any methodological effects which could have led to the appearance of false periodicities.

In order to illustrate the main results of our analysis, Fig. 2 presents the spectra and curves of the daily evolution calculated using the superposition method. Each plot of the daily evolution contains the distributions of the boundaries of 95% confidence intervals for three points: at the maximum, minimum, and at one of the points approximately in the middle of the range, calculated under the assumption of their normal distribution. Since the deviations from the normal model can notably distort the real confidence intervals, we also used some robust estimates. In particular, we applied different methods of smoothing, rank and sign criteria, and calculation of the daily evolution for different samplings from catalogs.

Estimate of the significance of spectral estimates is even a more complex problem and its exact solution is possible only at some a priori model suppositions. Therefore, we used only the robust estimates. The main method was calculation of spectra for various spatiotemporal samplings from the analyzed catalog: if any peak was found in the spectra of the major part of samplings, it was considered significant. In addition, if spectral peaks on the plots for each of the individual regions were not significant, the coincidence of the

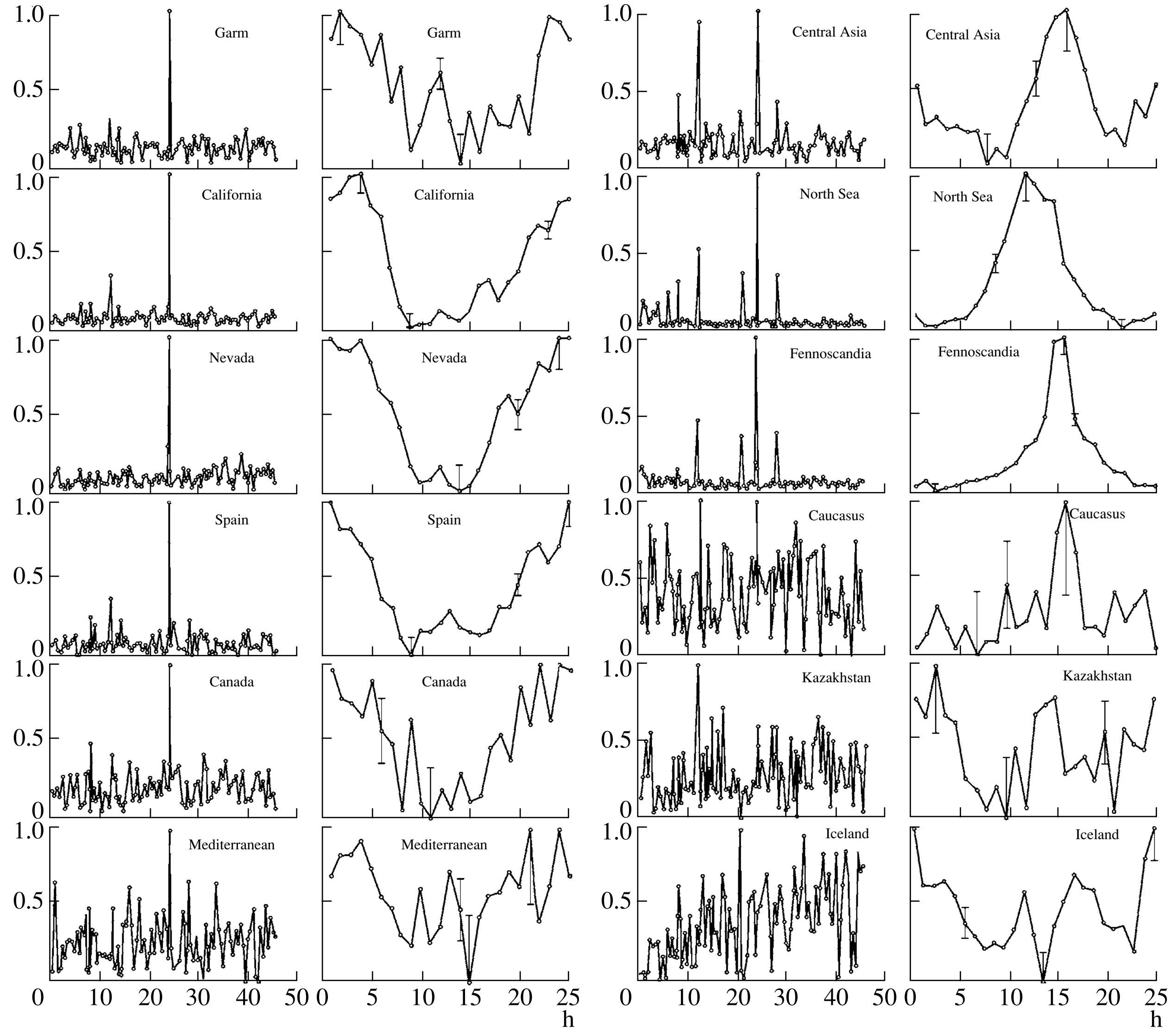

Fig. 2. Spectra reduced to one linear scale and diurnal cycle of seismicity in different regions. In each region, seismicity spectrum is shown on the left; diurnal cycle, on the right. Time of the day on the diurnal cycles is local, and zone time is given for the location of the gravitational center of earthquakes in each of the catalogs. Each plot of the diurnal cycle contains 95% confidence intervals for three points in the maximum, minimum, and one of the points approximately in the middle of the range.

parameters of these peaks in various regions could be considered as sufficient proof that the existence of the revealed phenomenon is real. Different catalogs are actually separate samplings from the general set of the data about the Earth's seismicity. Therefore, the coincidence of the peculiarities of spectra in Fig. 2 for practically all regions studied here is sufficient proof of the significance of the detected effects.

The plots shown in Fig. 2 can be categorized in three groups. The first group (Garm, California, Nevada, Spain, Canada, and the Mediterranean) is characterized by a prominent daily periodicity with a nighttime maximum of seismic activity. The second group (the North Sea, Fennoscandia, Central Asia, and the Caucasus) is also characterized by diurnal periodicity, but the maximal number of earthquakes occurs at daytime. The third group includes two regions lacking the daily periodicity: Kazakhstan, with a clear 12-h periodic component, and Iceland, with spectrum contaminated by strong noise.

In the analysis of the Garm catalog, we used two samplings of earthquakes with different energy classes K (or magnitudes M): $K > 6.5$ ($M > 1.4$) and $K \leq 6.5$ ($M \leq 1.4$). The analysis of the recurrence plot demonstrated that the second sampling contains unrepresentative events. In the spectrum of the second sampling, we found a sharp maximum at a period of $T = 24$ h, which notably exceeded the dispersion of the spectrum, and less manifested extrema at periods of 12 and 8 h. In the spectrum of stronger events, the diurnal peak only slightly exceeds the noise, and the peak becomes insignificant for the events with $K \leq 7.5$ ($M \leq 2.0$).

The spectrum of seismicity in California also contains a diurnal maximum with a high Q-factor and less representative extremum at $T = 12$ h. The extremum at $T = 8$ h is not distinguished. The maximum of seismicity is observed at night, with a shift from midnight to morning. Like in the GTA, the 24-h period rapidly disappears during the transition to stronger earthquakes. The diurnal periodicity is not distinguished for samplings with $M > 2.8$ ($K > 9$). The curve for the diurnal evolution is less noisy than in the GTA.

The spectrum of seismicity variations in Nevada contains one significant period $T = 24$ h. The diurnal cycle is very similar to that obtained in California, with the only difference that a decrease in activity by the morning is less sharp, while the increase in evening activity begins earlier. The reliability of distinguishing these harmonics rapidly decreases with the increase of the earthquake magnitude threshold in the sampling.

The seismicity spectrum in Spain is very similar to the spectra in the regions considered above. Significant periods in the spectrum are found at periods of 24, 12, and 8 h.

The seismicity spectrum for Canada includes periods of 24, 12, and 8 h. The diurnal cycle is equally noisy to that of the GTA, while the significance of the 24-h period sharply drops with the increase of the earthquake magnitude.

For the analysis of seismicity in the Mediterranean region, we used a catalog with a duration approximately equal to 3.5 yr. It is likely that the spectrum appeared very noisy owing to such short duration of the sampling. Although the values of spectral estimates at periods of 8, 12, and 24 h are greater than at the neighboring periods, they are distinguished only at the significance level limit.

In the earthquake spectrum of Central Asia, periods of 24 and 12 h are clearly seen, and the amplitudes of the corresponding peaks are practically equal. A period of 8 h is also present but with a smaller excess over noise. This territory is characterized by the fact that the diurnal seismicity cycle has the main maximum during daytime, whereas the secondary maximum is recorded at night, which is reflected in the spectra with a sharp increase of the 12-h component.

In the seismicity spectra of Fennoscandia and the North Sea, the periods of 24, 12, and 8 h are clearly manifested. However, extrema also exist at periods of 21 and 28 h. The nature of these extrema is not clear. We cannot exclude the influence of man-caused factors, which lead to the modulation of the diurnal cycle and appearance of beatings. The maximum of the daily cycle is at daytime. It is quite short for Fennoscandia and prolonged for the North Sea. The shape of the diurnal cycle of seismicity in the North Sea region coincides with that in Central Asia. However, the maxima are displaced by approximately 4 h (relative to each other).

In the available catalog of the Caucasus earthquakes, seismic events with $K > 7.8$ were completely represented. At the same time, the catalog also includes many weak earthquakes with $K \sim 6$ that were recorded on the Dzhavakhet Highland. They were also analyzed, because a denser network of seismic stations was located there.

The spectrum of the complete catalog appeared significantly noisy. If not for the data of other catalogs, one could make a conclusion about low significance of 24, 12, and 8 h periods. Precisely such behavior was typical of the spectra of catalogs considered after eliminating weak earthquakes. The Q-factor of the spectral extremum near 12 h is lower than the Q-factor of two other peaks. The curve of the diurnal cycle has a very complex shape with several peaks of activity of low significance. One stable peak of activity during the daytime is distinguished over this background. Its duration is notably shorter that the duration of other catalogs considered here, and the intensification or attenuation of activity is very sharp. The shape of the diurnal cycle of seismicity in the Caucasus coincides well with that in Fennoscandia.

The main peculiarities of earthquake spectra in Kazakhstan are the dominating role of 12-h period and the lack of a significant 24-h period. Two peaks are clearly seen on the curve of the diurnal cycle. In addition to the dominating nighttime peak, one can see a peak during the daytime with comparable amplitude.

Other than the regions presented in table and those considered above (Fig. 2), catalogs of six more regions were analyzed. All of them are related to the Pacific seismic belt: Alaska, Kamchatka, Japan, New Zealand, Pacific Ocean, and Chile. The 24-h period is presented in all these regions. However, the 12-h period is significant only for Kamchatka and Chile. The amplitude of the peak for this period in other catalogs is greater than for the neighboring harmonics. However, this excess is comparable with the level of the general dispersion of spectra. A similar pattern is also observed for the 8-h period.

In each of the six regions, the spectral extrema at a period of 24 h become insignificant with stronger earthquakes ($M > 2.5$). The maximum of seismicity occurs during the nighttime in three regions (Kamchatka, Alaska, and Pacific Ocean) and during the daytime in the other regions (Japan, New Zealand, and Chile). The Chile catalog is marked by a short period of seismic activity.

Iceland is the only region where the seismicity spectrum does not contain diurnal, semidiurnal, and 8-h harmonics. The seismicity spectrum of this region does not resemble any of the spectra discussed above, while the daily mean evolution strongly depends on the season. One of the possible causes of this fact can be, for example, a large contribution of volcanic earthquakes to seismicity, which were absent in other regions studied here.

Thus, the seismicity spectra for different regions of the world include significant peaks at periods of 24, 12, and 8 h, which exceed by many times the spectral values at other periods. However, none of the spectra contains significant peaks at the periods of lunar–solar tide other than 24 and 12 h. According to [8, 9], components of longer periods corresponding to the lunar–solar tide are absent in the GTA earthquake spectra.

The explanation of these surprising facts faces serious difficulties. A rapid decrease of the extrema with increasing strength of the earthquakes in the analyzed samplings give certain grounds to consider them as endogenous processes that can be related, for example, to the wind, thermal, or electromagnetic influence of the Sun on the Earth [10–14]. However, this interpretation cannot explain the opposite phases of the diurnal cycles of seismicity in proximal areas.

Another equally intriguing peculiarity of the results obtained here is the fact that the spectral peaks are extremely narrow and their Q-factor is high. For example, the width of the diurnal peak in the GTA seismicity spectrum is only about 4–5 min, which is approximately 300 times smaller than the length of the day. A search for the mechanisms of such resonances with high Q-factor in the seismicity spectra, regardless of the causes of their appearance, faces a principal difficulty. This is that if one process influences the other, the width of the corresponding extremum of the spectrum of the process (cause) is usually equal or smaller than for the process influenced by the cause. Only the self-resonance processes are exceptions. The existing concepts about the character of the processes of the Earth's crust deformation and their large inertia contradict the possibility of the high-Q seismicity response to external forcing.

In order to find out the possible mechanisms of the appearance of high-Q peaks in the seismicity spectra, it is first necessary to find the causes of the differences in the character of the diurnal cycle in different regions.

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