Effect of solar activity on electromagnetic fields and seismicity of the Earth

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Abstract. It is shown that bursts of intensity of ionizing electromagnetic radiation from the Sun, as well as geomagnetic storms, cause a statistically significant decrease in the total number of earthquakes on Earth. After bursts of ionizing radiation from the Sun, a statistically significant decrease in the total energy of earthquakes occurs, and after geomagnetic storms, its increase is observed. This is mainly due to an increase in the number of the strongest earthquakes with $M_S > 7$ after geomagnetic storms and a decrease in the number of such earthquakes after bursts of ionizing electromagnetic radiation from the Sun. During geomagnetic storms and for several days after them, the probability of occurrence of strong earthquakes increases more than two times, and after bursts of ionizing electromagnetic radiation from the Sun, this probability decreases almost twice.

1. Introduction

Back in 1853, the world famous astronomer Rudolph Wolff suggested that an increase in solar activity (SA) could affect the seismicity of the Earth. However, extensive studies of the effect of processes occurring in the Sun and in near-Earth space on the state of the earth's crust and seismicity began 50-60 years ago, when the development of instrumental observations on Earth and in near-Earth space made it possible to obtain large amounts of data necessary for such studies. Over the years, a number of works have been devoted to this topic. Such interest is due to the fact that new results obtained in this direction can help to more accurately predict periods of increased seismic hazard on Earth, to study the effect on seismicity of factors of different physical nature and to more fully understand the regularities of solar-Earth connections. However, the published results are often contradictory (see, for example, reviews and results of works [1-3]). Questions about the root cause and physical mechanism of the SA influence on the seismicity of the Earth also remain debatable. Therefore, it is important to continue experimental research in this direction.

2. Methods

For this purpose, the changes in the global seismicity of the Earth from 1973 to 2001 were studied and compared with the SA variations. This choice of the time interval was due to the presence of representative data on seismicity and a number of parameters characterizing the SA. The NEIC global seismicity catalog was used as a source material for seismicity analysis. It contains the date-time, the magnitude ($M_S$), coordinates and depth of the hypocenter of 320 thousand earthquakes that
occurred during the period under consideration. Earthquakes with $M_s > 4.4$ are representative, of which there were more than 130 thousand. To analyze the SA, the data published by NOAA were used: catalogs of geomagnetic storms, data on the solar plasma velocity of the IMP-8 satellite, whose orbit was located outside the Earth's magnetosphere, and data on the intensity of the solar electromagnetic radiation (ER) flux in the radio frequency range. At the first stage, these data were used to study the change in seismicity after magnetic storms (MS). However, we failed to identify any noticeable changes in seismicity after the MS. It can be assumed that the induced changes are so small that they are very difficult to detect against the background of natural variations in seismicity.

Therefore, to detect possible changes in seismicity, the epoch superposition technique was used. Seismicity was considered within time windows of ± 30 days from the onset of each of the storms, which were then superimposed in time. The times of the beginning of each of the geomagnetic storms were used as reference points for the selection of those windows. The date and time of all earthquakes that occurred within each windows were replaced by the time recalculated relative to the start of the corresponding storm, and their energy ($J$) was calculated from the magnitudes $M_S$ using the known relation

\[ \lg E = 1.5 \cdot M_S + 4.8. \]  

All those data was combined into a common new catalog which was used for further processing.

Then the time window was divided into short successive intervals, and the mean seismic energy and the number of earthquakes that occurred within each of them were calculated. The time corresponding to the middle of each of such intervals, counted from the beginning of the MS, was calculated too. After that, the dependences of the number of earthquakes and their mean energy on time were analyzed. The mean values of their for the entire time before magnetic storms (background level) and their mean values after the beginning of the MS were estimated, as well as their difference. To evaluate the statistical significance of changes in the mean number of earthquakes and their energy after magnetic storms, the nonparametric Wilcoxon test was used. The total seismic energy (SE) of all earthquakes that occurred before and after the MS was calculated too.

3. Results

In first, the change in the number of earthquakes over time was studied using this technique. Figure 1 shows the 1071 MS-averaged dependences of the daily number of earthquakes on the time before and after the MS, obtained both using earthquakes of only representative magnitudes and using all seismic events presented in the catalog. It follows from it that in the first 5 days after the MS there is a noticeable decrease in the number of earthquakes, and after 5-6 days their number increases again, while remaining below the background level. It is unexpected that the decrease in seismicity began at least 2-3 days before the onset of magnetic storms. A more detailed analysis shows that the decrease in the number of earthquakes begins 3-5 days before the MS (see Fig. 1c). Consequently, magnetic storms could not be its cause in this time interval.

Magnetic storms occur on Earth several days after solar flares and coronal mass ejections, which is due to the relatively low speed of propagation of solar plasma. However, the electromagnetic radiation (ER) of the Sun reaches the Earth in just 8.2 minutes, which could suggests that it is the reason for the change in seismicity before MS. According to data of the IMP-8 satellite, the velocity of the solar plasma front at the boundary of the Earth's magnetosphere during the occurrence of the magnetic storms under consideration was in the range of 309 - 1040 km / s. Consequently, the delay time of the MS relative to the ER burst should be within 1.6-5.6 days. This is in good agreement with the time by which the seismicity decay is ahead of the onset of MS.

Therefore, the same technique was used to study the change in the intensity of the solar radiation flux in the radio frequency range, which is often used as a measure of its ionizing radiation (ultraviolet, X-ray, etc.), and an indicator of the density of charged particles in the ionosphere. Figure 2a shows the change in ER before and after MS. It can be seen that the flow intensity has a single maximum, which is three days ahead of the MS, which coincides in time with the onset of seismicity suppression in Fig. 1a and 1b. All this confirms the above assumption.
In this connection the dependence of the ER flux on the time before and after those events on the Sun, which caused the occurrence of the considered magnetic storms, is of interest (Fig. 2b). The times of their beginning were defined as

\[ T_j = t_j - \frac{S_e}{v_j}, \]

where \( t_j \) is the time of the \( j \)-th MS taken from the catalog of magnetic storms, \( v_j \) is the velocity of the solar plasma front recorded at the same time at the boundary of the Earth's magnetosphere by the IMP-8 satellite, and \( S_e \) is the distance from the Sun to the Earth. When comparing Fig. 2a and Fig. 2b, one can be seen that the maximum in Fig. 2b becomes sharper and coincides in time with solar events that caused magnetic storms. Consequently, bursts of ER intensity should more accurately indicate the moments of the effect of the Sun's electromagnetic radiation on the seismicity of the Earth.

Therefore, instead of magnetic storms, the times of a sharp increase in the ER intensity were used as reference points for choosing time windows. Formally, they were defined as times in which the rate of increasing of the solar radio emission flux (\( dW/dt \)) exceeded the 95% confidence interval. In total, during the time interval under consideration, 949 sharp bursts of ER were detected, which is comparable to the number of magnetic storms.

Figure 3 shows the number of earthquakes before and after these bursts as function of time, obtained from earthquakes of representative magnitudes (Fig. 3a) and from all events in the catalog (Fig. 3b). They clearly show that after an increase in the ER intensity, there is a sharp decrease in the number of earthquakes, which coincides with them in time (this is even better seen in Fig.3c, which shows a fragment of the last dependence with a width of ± 3 days, plotted with a higher time resolution). Immediately after the bursts, the number of earthquakes decreases, and after 2-3 days it...
begins to increase smoothly. Nevertheless, for 10 days, their number remains below the background level.

![Graphs](image)

**Fig. 3.** Time change in the number of earthquakes of representative magnitudes (a) and all events presented in the catalog (b), before and after sharp bursts of ER and the similar dependence plotted in a window of ±3.2 days with a higher time resolution (c).

![Graphs](image)

**Fig. 4.** Mean energy of earthquakes before and after the ER bursts as function of time (a), a similar dependence obtained using the ER bursts, before and after which the MS were not appear (b), and a similar dependence obtained using the MS, before and after which the ER bursts were not recorded (c). Earthquake energy (W/m²) shown using logarithmic scale.

Table 1 presents numerical estimates of the change in the number of earthquakes that were observed in Figures 1 and 3. One can see that the decrease in the number of seismic events after the MS is only about one percent of the background level. Bursts of ER have a stronger effect, especially in the first three days. After them, there is a decrease in the number of earthquakes by almost 6%. Despite the fact that the detected changes in seismicity are very small, they are statistically highly significant. This can be seen from the estimates of their statistical significance presented in the table, which turned out to be much less than the value of 0.05, usually taken in geophysics as the level of significance.

Thus, some suppression of the global seismicity of the Earth is observed both after the MS and after the ER. Despite this, the mean and total energy of earthquakes is increasing, and not by a few percent, as was the case with the number of earthquakes, but by tens, which follows from Table 2, where their estimates are presented. However, such changes are not statistically significant (since the significance is significantly greater than 0.05). Figure 4a, which shows as an example the time dependence of the mean energy of earthquakes before and after ER, shows what this may be related to. One can see that after ER, the mean energy of earthquakes changes over time in a very disordered manner. In the first two days, it noticeably decreases relative to the background level. In the next two days, on the contrary, it increases, then falls again, etc. At the same time, its variance increases.
Table 1. Changes in the mean number of earthquakes (ΔN) and their statistical significance (P) after ER and MS within time windows with a width of ± 10 and ± 3 days

| Trigger | ΔN, % | P   |
|---------|-------|-----|
| MS      | -1.1  | 0.0023 |
| ER      | -2.5  | 0.0002 |
| ER (±3 d) | -5.7  | 0.0001 |

Table 2. Changes in the mean energy of earthquakes (ΔE) after MS and ER, their statistical significance (P) and the ratio of the total energy (E_a/E_b) of earthquakes that occurred after and before them, and similar estimates obtained for magnetic storms, before and after which ER bursts were not recorded, and obtained for ER bursts, before and after which MS was not observed.

| Trigger | ΔE, % | P  | E_a/E_b |
|---------|-------|----|---------|
| MS all  | 57.1  | 0.082 | 1.55    |
| ER all  | 33.6  | 0.089 | 1.32     |
| MS no ER | 58.5  | 0.049 | 1.52     |
| ER no MS | -70.8 | 0.043 | 0.27     |

It can be assumed that this occurs as a result of the opposite effect on the mean energy of earthquakes of MS and ER. However, the estimates of the change in the mean energy after MS and ER, at first glance, do not confirm this (see Table 2). Nevertheless, it cannot be ruled out that this is due to large errors in their determination, which were the reason for their low statistical significance.

Therefore, the effect of these two factors on the energy characteristics of seismicity was studied separately. For this purpose, from the total number of ER bursts, only those were selected, before and after which there was no MS. Changes of the mean energy of earthquakes before and after electromagnetic bursts as function of time were studied using the selected ER bursts as a reference for the choice of time windows. Figure 4b, in which shows those change versus time, shows that immediately after electromagnetic bursts, there is a sharp decrease in the energy of earthquakes.

The change in the mean energy after magnetic storms was studied in a similar way. From their total number, only those storms were sampled, before and after which no intense bursts of ER were recorded. Using them the dependence characterizing the time change in the mean energy of earthquakes before and after magnetic storms in the absence of ER bursts was obtained (Fig. 4c). In contrast to the previous case, an increase in the mean energy of earthquakes is observed here, which occurs after magnetic storms with a delay of several days.

Numerical estimates of the observed changes in the mean earthquake energy (ΔE) after ER and MS are also presented in Table 2. One can see that the impact of ER leads to a decrease in the mean earthquake energy relative to the background level by almost 71%, and magnetic storms cause its increase by 58.5 %. Note that these changes are already statistically significant, since in both cases the significance turned out to be less than 0.05. The same conclusions follow from the analysis of the values of the ratio of the total energy of all earthquakes that occurred after and before the MS (E_a/E_b) presented in the same table. Thus, after the ER bursts, there is not only a decrease in the number of earthquakes, but also in their energy. However, after the MS, the number of seismic events also slightly decreases, but their energy, on the contrary, significantly increases.

For practical applications, it is important to understand what changes cause being the effect of these factors in distribution of earthquakes over their energies. To do it, the number of earthquakes that occurred before (N_b) and after (N_a) ER bursts was calculated using seismic events of various
magnitudes $M_S$. Their ratio $N_a/N_b$, which characterizes the change in the number of such seismic events after ER bursts, was calculated too. Figure 5 shows these ratios as a function of earthquake magnitudes. Similar dependence the ratio of number of earthquakes that occurred after and before magnetic storms is shown too. One can see that the number of weak and moderate seismic events with $M_S < 7$, both after ER and after MS, changes very insignificantly. However, the number of strong earthquakes with $M_S \geq 7$ after ER decreases almost 4 times, and after MS, on the contrary, increases more than 3 times. The latter circumstance is consistent with the results of [4-6], in which it was noted that number of earthquakes with $M_S > 6.5-7.0$ increase after magnetic storms.

![Fig. 5. The ratio of the number of earthquakes ($N_a/N_b$) that occurred after and before the ER bursts (dotted line), and after and before the MS (solid line), depending on their magnitude.](image)

These results were verified in another way. For this, the time dependences of the number of strong earthquakes with magnitude $M_S > 7$ were analyzed before and after ER and MS. As before, those ER bursts only, before and after which there were no MS, and those magnetic storms, before and after which no ER bursts were recorded, were used for this. Since there are relatively few strong ($M_S > 7$) earthquakes, the observation period was extended. Seismic events that occurred in the interval 1973-2020 were considered. There were 349 earthquakes in total.

The resulting dependences of the number of earthquakes on time are given in Figure 6. The same figure shows the mean values of the number of earthquakes before (background level) and after the effect of the factors under consideration. It clearly shows that immediately after bursts of ionizing radiation from the Sun, the number of earthquakes with $M_S > 7$ noticeably decreases (Fig. 6a). On the contrary, after geomagnetic storms, the activation of such earthquakes is observed, which occurs with a delay of several days (Fig. 6b).

In addition, the effect of the combined impact of MS and ER in their various combinations studied. In most cases, the changes identified above were blurred. However, for magnetic storms, before which ER bursts were recorded for three days or less, and the rest of the time they were not observed, a more distinct result was obtained. In Figure 6c, where it is presented, it can be seen that...

![Fig. 6. Time change in the number of earthquakes with $M_S < 7$ that occurred before and after ER (a), MS (b) and the simultaneous impact of these two factors (c).](image)
after the combined effect, a sharp activation of earthquakes with $M_s > 7$ occurs, which lasts only about three days. Unlike the previous case (Fig. 6b), seismicity increase begins immediately after the MS, without a noticeable delay.

Numerical estimates of changes in the mean number of such earthquakes are presented in Table 3. One can see that the impact of ER causes a statistically significant decrease in the number of earthquakes with $M_s > 7$ by 46% from the background level. On the contrary, after magnetic storms, their number increases statistically significantly by 32%. But the strongest increase in the number of earthquakes (by 55%) occurs after MS, immediately before which there were intense bursts of ionizing radiation from the Sun. However, in this case, the statistical significance is very small. This is due to the fact that the observed activation of seismicity lasts only three days. In this time interval, the increase in the number of earthquakes relative to the background already reaches 133%, and the significance estimate is 0.035.

**Table 3.** Time changes in the number of earthquakes with $M_s > 7$ that occurred on Earth over the period 1973-2020, before and after intense bursts of solar ionizing electromagnetic radiation (ER), of geomagnetic storms (MS), as well as before and after of simultaneous exposure these two factors (MS+ER), and a a similar dependence for the time interval ± 3 days.

| Trigger  | $\Delta N, \%$ | $P$   |
|----------|----------------|-------|
| ER       | -46.3          | 0.024 |
| MS       | 32.0           | 0.013 |
| MS+ER    | 55.0           | 0.154 |
| MS+ER, 3 d | 133.3          | 0.035 |

4. Conclusion

The above results show, first of all, that the processes occurring on the Sun affect the seismicity of the Earth and, consequently, the state of its lithosphere. However, the picture of their interaction is very complex. Factors of different physical nature, generated by solar activity, can affect the Earth's lithosphere and its seismicity in different directions. The impact of intense bursts of ER leads to a decrease in the probability of catastrophic earthquakes by almost two times, and magnetic storms, on the contrary, to an increase in this probability by almost a third. But it increases most strongly, more than twofold, after magnetic storms, before the onset of which, during a three-day interval, bursts of the intensity of ionizing radiation from the Sun were recorded (Table 3). Consequently, the results of the impact of these factors on the state of the lithosphere and its seismicity can vary depending on their combination.

The suppression of seismicity is observed after ER without a noticeable delay (Fig. 4b and 6a), and its activation after MS occurs after 2-5 days only (Fig. 4c and 6b). The latter circumstance was noted earlier during artificial irradiation of the earth's crust with powerful electromagnetic pulses, after which the activation of seismicity also occurred with a delay of 2-5 days [7-9]. Irradiation caused an increase in the rate of seismotectonic strain, which contribute to the process of quasi-plastic deformation of the crust that accelerated the relaxation of elastic stresses accumulated in it [8, 9].

ER bursts cause an increase in ionization of the ionosphere, which affects the parameters of the global electrical circuit, leads to a change in the activity of world thunderstorm centers, and worsen the conditions for the propagation of radio waves from natural and man-made sources. This reduces the intensity of the electromagnetic background over vast areas, which can cause suppression of seismicity due to a decrease in the triggering effect of electromagnetic fields. In turn, this can slow down the relaxation of elastic stresses in the crust.

Propagation of radio waves deteriorates during the MS too. However, they have a stronger triggering effect on areas in which strong earthquakes are prepared. Telluric currents induced in the
crust by changes in the geomagnetic field can initiate strong earthquakes in unstable areas of the
earth's crust [1,6]. Another reason can be the phenomenon of magnetoplastics. The rate of plastic flow
of rock bulk can change with a change in the geomagnetic field, which can also have a trigger effect
on unstable areas of the earth's crust [10].

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