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Long-period trends in global seismic and geomagnetic activity and their relation to solar activity

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Abstract

In the present paper, we are comparing the century-scale trends and decadal variations in seismic activity, and are looking for a relation to century-scale and decadal changes in solar and geomagnetic activity. The possible mechanisms of solar activity influences on seismic activity are also discussed.

Keywords: Solar; Seismic and geomagnetic activity

1. Introduction

Many terrestrial processes exhibit long-term changes and trends: global temperature, geomagnetic activity, Earth rotation rate, etc. A challenging task is to look for a relation between them, and to identify possible extraterrestrial factors contributing to such long-term changes. The strongest energy source near the Earth is the Sun, so it is natural to look for a possible connection between different elements of solar activity and terrestrial processes. In the present paper we study the possible influence of solar activity on the occurrence rate and energy of earthquakes. In Section 2 we are presenting the secular and decadal variations in solar and seismic activity. In Section 3 we will look for day-to-day variations in the number of the earthquakes relative to the possible solar activity agents supposed to trigger them. In Section 4 we estimate the energy released in earthquakes. In Section 5 we compare the long-term variations in seismic activity and atmospheric circulation. The results are summarized and discussed in Section 6.

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2. Secular and decadal variations in seismic activity

The century-scale variations in solar activity are well known—the so-called Gleissberg cycle (Gleissberg, 1939). Geomagnetic activity also exhibits century-scale variations. The aa index of geomagnetic activity (Mayaud, 1973) covers the period from 1868 to present, and its long-term variations are highly correlated to the long-term variations in sunspot activity. Lockwood et al. (1999) found a doubling in the geomagnetic field in the last century, and related it to the increase in the solar magnetic field. Later Makarov et al. (2002) found a doubling in the area of polar zones of the Sun occupied by unipolar magnetic field during 1878–1996, and speculated that the behavior of aa index can be related to the increase in the polar cap area and consequently in the solar magnetic flux from open magnetic field regions in polar coronal holes. According to Richardson et al. (2002), the increase in the geomagnetic activity is due to the increase of the velocity of the slow solar wind.

In an earlier investigation we (Georgieva et al., 2002) studied the long-term variations in seismic activity in the Mediterranean region over a period of seven centuries. The historical data about earthquakes were taken from the catalogue of ancient earthquakes in the Mediterranean area up to the 10th century (Guidoboni, 1994), in which information is gathered from ancient books and chronicles about earthquakes and seismic sea-waves, as well as other geophysical and geomorphological phenomena such as emergence of islands, subsidences, and landslides. For sunspot activity, the estimations of Schove (1955) were used for the years of minima and maxima of the 11-year solar activity cycle, together with the approximate values of the maxima. Schove's data set covers the period from 649 BC to present, however the set is continuous only since 296 AD. Therefore, though data from 760–750 BC to 995 AD for earthquakes are available, only the ones between 296 and 995 AD were used in the study. This period covers seventy 11-year solar cycles grouped in several secular (Gleissberg) solar cycles. In Fig. 1 the estimated value of the sunspot number in the maximum of each 11-year cycle is compared to the total number of earthquakes in this cycle, from the minimum preceding, to the minimum following the maximum. This data set is smoothed by three-point running mean to filter out the higher frequencies and to eliminate the random fluctuations. Again, as in the case of geomagnetic activity, highest seismic activity is seen around secular solar maximum. The correlation between the variations in solar activity and the number of earthquakes is 0.47. This correlation is not very high as obviously solar activity is by far not the only factor affecting seismic activity. Still, the correlation is highly statistically significant, with $p < 0.01$, even as both data sets are based on fragmentary records and indirect estimations, and it holds over a period of seven centuries. Therefore we can suggest that there may be a connection between solar activity and seismic activity.

To verify this suggestion, we next study the relation between solar activity and the number of earthquakes in the 11-year sunspot cycle which is the most prominent cycle of solar activity. Since the beginning of the 20th century we have reliable data about the strong earthquakes worldwide. This period includes nine full 11-year solar cycles for which we have the global yearly number of strong (with magnitude 7 or greater) earthquakes, provided by the National Earthquake Information Center, World Data Center A for Seismology (available from: <http://neic.usgs.gov/neis/eqlists/7up.html>). As a measure of solar activity we use the yearly international sunspot numbers provided by <http://ngdc.noaa.gov/stp/SOLAR/SSN/>. Fig. 2 presents a superposed epoch method analysis of the global yearly number of earthquakes and the international sunspot number. Two maxima in the average yearly number of earthquakes are seen—one coinciding with sunspot maximum (year 0), and a second one on the descending phase of the sunspot cycle (year + 3), three years after the sunspot maximum.

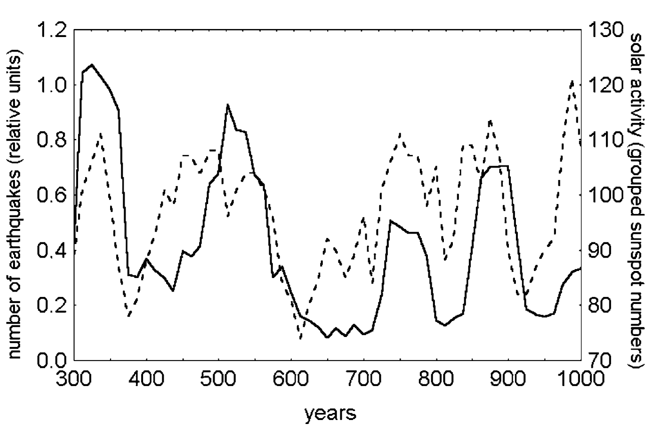

Fig. 1. Number of earthquakes in the Mediterranean area summed over the 11-year solar cycles (solid line) and solar activity in the maxima of the solar cycles (broken line) in the period 296–1000; 3-point running means.

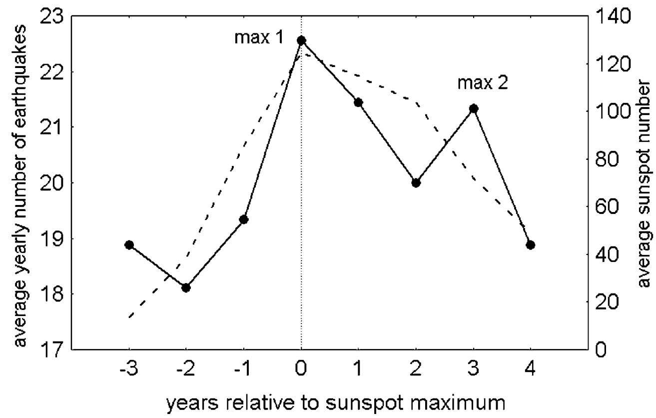

Fig. 2. Average number of earthquakes (solid line) and solar activity (broken line) in the 11-year solar cycle for the period 1900–1999.

To estimate the statistical significance of this result, the means of the number of earthquakes in these two maxima (22.6 with a standard deviation $S = 8.0$, $n = 9$, and 21.3 with $S = 9.08$, $n = 9$, respectively), were compared to the overall mean yearly number of earthquakes with $M \geqslant 7$ in the 100 year period studied (20.05 with $S = 7.23$, $n = 100$), and to the average yearly number of earthquakes in the 10 years of sunspot minimum (19.0 with $S = 7.15$, $n = 10$). For this comparison, the modified Student's t-test for small samples was used.

$$t_1 = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\frac{S_1^2 n_1 + S_2^2 n_2}{n_1 + n_2 - 2} \, \frac{n_1 + n_2}{n_1 n_2}}}$$

Even if we apply the harder criterion and compare the average number of earthquakes in the years of sunspot maximum to the average number of earthquakes in all years studied ($n = 100$), this gives $t_1 = 2.64$ and $p < 0.05$. The maximum in year (+3) is less significant when compared to the 100-year average ($p < 0.1$) but is well pronounced and is still highly significant ($p < 0.05$) when compared to the average number of earthquakes in solar cycle minimum.

3. Solar drivers of seismic activity

The distribution of the number of earthquakes in the 11-year cycle is very similar to the variations in geomagnetic activity which also has two maxima in the sunspot cycle: one in sunspot maximum, and another on the declining phase of the sunspot cycle. This similarity in the relation of seismic and geomagnetic activity to solar activity on both secular (Glaissberg cycle) and decadal (sunspot cycle) time-scales leads us to suppose that the same agents of solar activity may be responsible for geomagnetic and seismic activity. Geomagnetic activity in sunspot maximum is predominantly caused by the large number of solar coronal mass ejections (CME's), and on the declining phase the main solar agent for geomagnetic activity is the high speed solar wind (HSS) from polar coronal holes (Gonzalez et al., 1999). We will therefore study the day-to-day variations in the number of earthquakes relative to the days when the Earth is exposed to HSS's and CME's.

The number of earthquakes with $M \geqslant 7$ or above which we used to study the solar cycle variations in the earthquakes occurrence is quite low—on the average 18 per year, so they are not suitable for a day-to-day comparison. For this reason for the present investigation we use the daily numbers of moderate ($M \geqslant 5.5$) earthquakes provided by the National Earthquake Information Center (<http://quake.geo.berkeley.edu/cnss/>).

3.1. High speed solar wind

We define the days of arrival to the Earth of high speed solar wind as days with an abrupt (by at least 100 km/s in no more than a day) increase in the solar wind velocity to no less than 500 km/s, accompanied by a drop in solar wind density and increase in the temperature. These are the characteristics of solar wind from solar coronal holes. In the period 1973–2000 we have identified 307 cases of high speed solar wind. Fig. 3 is a superposed method analysis for the average daily number of earthquakes on the days of arrival of high speed solar wind (day 0), 1 day before and after the arrival of the high speed solar wind (day −1 and +1, respectively), etc. A well pronounced maximum in the number of earthquakes is seen in the day of arrival of high speed solar wind and one day after it.

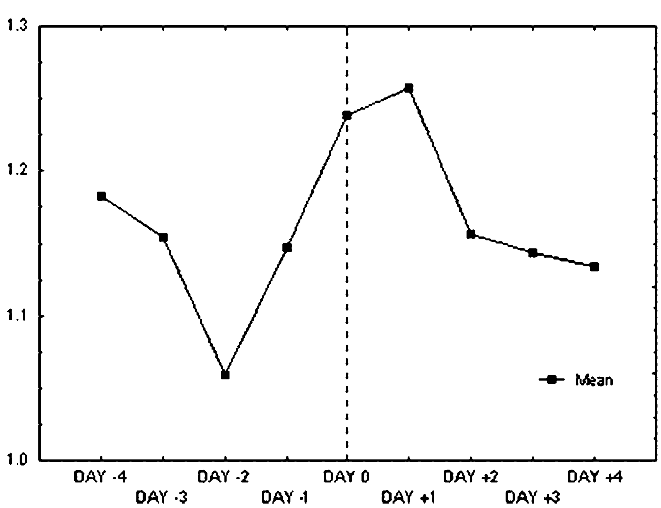

Fig. 3. Average daily number of earthquakes on days with high speed solar wind (day 0), one day before and after the arrival of high speed solar wind (day −1 and +1, respectively), etc.

The statistical significance of the difference between the occurrence of earthquakes on different days relative to the days of arrival of high speed solar wind is evaluated by means of Factor Analysis (Statistica for Windows, StatSoft, Inc.). This statistical method is applied to detect structures in variables—to check whether the variables are grouped by one or more "factors", or in other words, whether they belong to one or more populations. It is based on the assumption that relationships between observed variables are due to the effects of underlying unobservable factors, and that variables with similar values of the factors are in some way similar. If only one factor grouping the variables is extracted by the analysis, then they belong to the same population. In case of two or more factors, variables with differing values of the factors belong to different populations. In a graphical presentation, the more separated the variables are in the space of the factors, the more different they are.

We divide our data set of daily number of earthquakes into four variables. The first variable is the number of earthquakes on days of arrival of high speed solar wind ("SW"). The second variable is the number of earthquakes on the day following the arrival of high speed solar wind ("SW + 1"). As Sytinskii (1997) has found that in the period 1976–1982, more earthquakes tend to occur one day before the day of the maximum of solar wind speed, our third variable is the number of earthquakes on the day before the arrival of high speed solar wind ("SW − 1"). And in the forth variable we include all the remaining days ("RANDOM"). The analysis extracts two factors grouping the variables, and Fig. 4 presents the distribution of these variables in the plane of the factors.

It can be clearly seen that the days of arrival of high speed solar wind and the days immediately following them (SW and SW+, respectively) are grouped together, and are very different from all other days. This means that the day

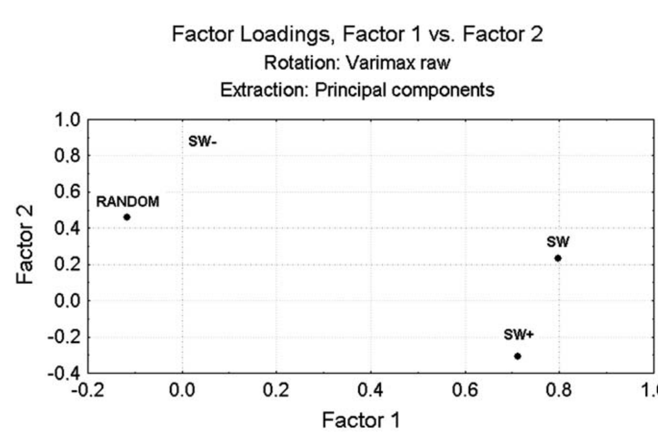

Fig. 4. Factor loadings for the variables SW, SW+, SW− and RANDOM (see text).

of arrival of high speed solar wind and the day following immediately after it are "special" concerning the earthquake appearance. On the other hand, the day before the arrival of high speed solar wind does not differ in any way from all other days. Probably the reason why Sytinskii (1997) found an increase in seismic activity on day "−1" is the criterion for days with high speed solar wind which he used—days preceded by at least 24 h of solar wind with velocity not less than 500 km/s, while we also require the velocity of at least 500 km/s to be reached, but relieve the requirement for no less than 24 preceding hours of high speed wind, and define the day of the high speed solar wind as the day of the sharp jump in the wind velocity.

3.2. Coronal mass ejections

Coronal mass ejections (CME's) are enormous loop-like bubbles of plasma expelled from the Sun. Their size at the Earth's orbit is about 0.25 AU, and they are characterized by low magnetic field fluctuations, low proton temperature, composition anomalies and bidirectional suprathermal electron fluxes indicating that both ends of the magnetic field lines are rooted on the Sin. CME's may have the velocity of the ambient solar wind, or may be significantly faster, in the latter case driving a shock and a sheath with high velocity, temperature and density, and high magnetic field magnitude and fluctuations. For our statistics we use the CME list of Cane and Richardson (2003) which includes the CME's observed near the Earth in the period 1996–2000. Fig. 5 presents the superposed epoch analysis of the number of earthquakes with $M \geqslant 5.5$ relative to the days with CME's. The result is quite surprising. It seems that on days with CME's there is a well expressed minimum in the number of earthquakes. But a comparison with Fig. 3 shows that in fact on the days around the CME day, the number of earthquakes is even bigger than on days with HSS's, while their number on days with CME's is reduced relative to the higher level of these surrounding days. The statistical significance of this result is $p \leqslant 0.02$. Probably the high number of earthquakes around the days with CME's is due to the high geoeffectiveness of the shock/sheath region (e.g., Huttunen et al., 2002). It is known that the shock is a much larger scale structure than the CME itself (Sheeley et al., 1985). The bigger number of days with enhanced number of earthquakes around the days with CME's can explain why the maximum in the earthquake occurrence at sunspot maximum when is the maximum of CME's is higher than the earthquake occurrence maximum on the descending phase of the sunspot cycle when is the maximum of HSS's. However, at present we are unable to explain the lull on the very day of CME encounter, like in the eye of a cyclone.

4. Energy released in earthquakes

The energy released in earthquakes is calculated from the expression (Kanamori, 1977):

$$\log E = 1.5M + 4.7$$

where E is expressed in Joule units. Fig. 6 presents the solar cycle distribution of the average yearly energy released in earthquakes. Maximum energy is released during the third year after sunspot maximum, coinciding with the maximum in the high speed solar wind from solar coronal holes. On the other hand, in sunspot maximum the energy released in earthquakes has a minimum though their number has a maximum. As the energy is an exponential function of the magnitude, one strong earthquake has a much greater energy than numerous weaker ones. This means that solar activity in sunspot maximum triggers many weaker earthquakes while the high speed solar wind from coronal holes leads to fewer but much stronger ones. It is well known that the higher the magnitude of the earthquakes, the less is their number. According to Gutenberg–Richter law, the total number of earthquakes with magnitude M is proportional to 10^{-bM}, where b is a parameter which varies from area to area and is close to 1.

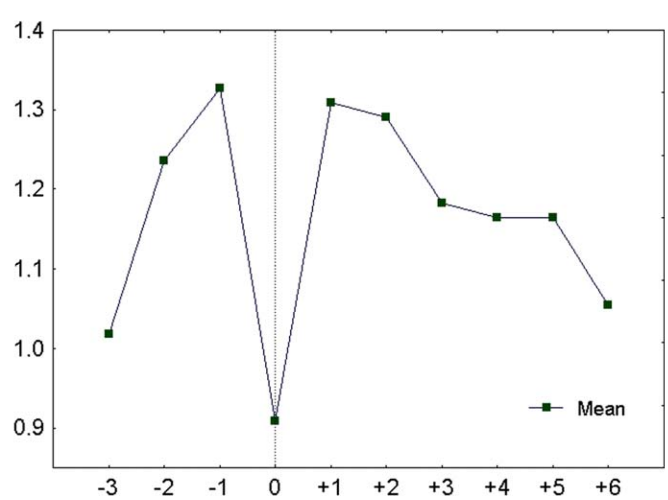

Fig. 5. The same as Fig. 3 for days with CME's.

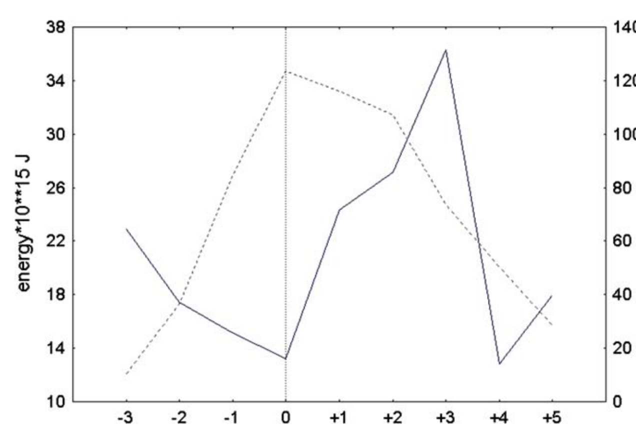

Fig. 6. Average yearly total energy released in earthquakes and solar activity (broken line, right scale) in the 11-year solar cycle for the period 1900–1999.

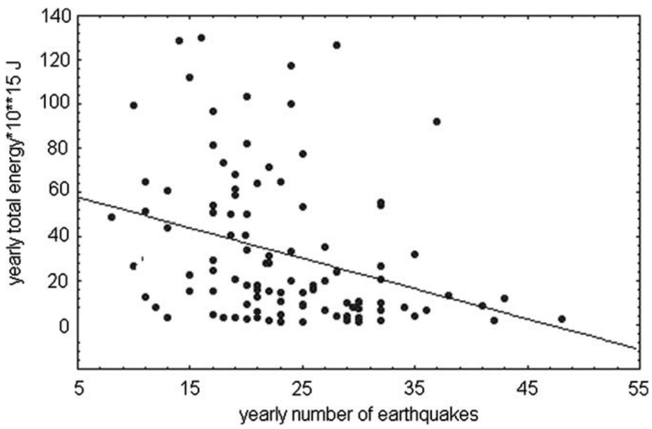

Fig. 7. Dependence of the yearly total energy released in earthquakes on the yearly number of earthquakes for the period 1900–1999.

Fig. 7 demonstrates that this is also true for the yearly distribution of earthquakes—high energy is released in years with few earthquakes, while in years with very big number of earthquakes, the total released seismic energy (respectively, the magnitude of the earthquakes) is not high. Maybe the reason is that when earthquakes occur often, energy is released before greater energy has been stored. However, in years with many high speed solar streams, the number of earthquakes is bigger than average, still their magnitudes are high.

5. Atmospheric circulation and seismic activity

Studying the list of earthquakes, it can be seen that often an earthquake in the course of several hours to a day is followed by one or more earthquakes at almost the same latitude and at increasingly higher (Eastern) longitude. This coincides with the direction of the large-scale zonal atmospheric circulation. Sytinskii (1997) suggested that the atmosphere is a mediator of the solar influences on seismic activity, through solar activity induced changes in atmospheric circulation, redistribution of pressure and disruption of the pressure balance on tectonic plates. To check the relation between the atmospheric circulation and seismic activity, we have compared the long-term changes in the strength of zonal circulation expressed by the temperature contrast between the equatorial and polar regions (Georgieva et al., 2002), anomalies with respect to the period 1961–1990, and the number of earthquakes with $M \geqslant 7$ in the last century (Fig. 8). The strengthening of western winds (i.e., increased transfer of air masses from east to west) is accompanied by an increase in the number of earthquakes.

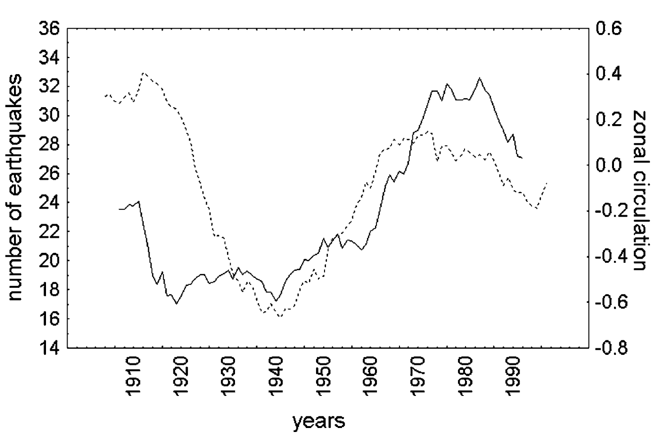

Fig. 8. Yearly number of earthquakes with $M \geqslant 7$ in the period 1900–1997 (solid line) and intensity of zonal circulation (broken line).

6. Discussion and conclusions

We have shown that on both secular (Gleissberg) and decadal (11-year solar cycle) time-scales, there is a connection between solar activity and seismic activity. There are more earthquakes in the secular solar maxima than at lower solar activity. Two maxima in the number of earthquakes are observed in the 11-year solar cycle—a higher one in sunspot maximum, and a secondary one on the descending phase of the cycle. The variations in seismic activity relative to solar activity are the same as the variations in geomagnetic activity, so probably the factors influencing them are the same. We have identified two solar activity agents responsible for triggering earthquakes: coronal mass ejections which are the cause of the greatest geomagnetic disturbances around sunspot maximum, and high speed solar wind from solar coronal holes which lead to the second geomagnetic activity maximum in the sunspot cycle. Coronal mass ejections lead to numerous weaker earthquakes at sunspot maximum, while high speed solar wind triggers the strongest earthquakes on the descending phase of the sunspot cycle.

Most of the studies devoted to the extraterrestrial factors influencing seismicity deal with tidal forces resulting from gravitational interaction between the Earth, Moon and Sun (i.e., Kulanin, 1984; Lopez et al., 1990; Dionysiou et al., 1994; Souchay and Stavinschi, 1997; Greff-Lefftz and Legros, 1999; Wu et al., 2001), however Vidale et al. (1998) showed the lack of earthquake correlation with tides.

Sytinskii (1997), based on the case study of several strong earthquakes, suggested that the triggering mechanism for earthquake occurrence is not the tidal force but the solar induced change in atmospheric circulation expressed in large-scale reorganization of baric fields, and showed that the energy of these disturbances is at least 3 orders of magnitude greater than the energy of an earthquake. As a solar activity agent inducing these changes he identified high speed solar wind (Sytinskii, 1989). Based on the data between 1968 and 1977, he found that the times of strong ($M \geqslant 6.5$) earthquakes coincide with the times of the arrival to the Earth of high speed solar wind, with earthquakes most often occurring one day before the dates with maximum speed of the solar wind.

Several studies have demonstrated the reality of this possible relation. Bucha and Bucha (1998) found that downward winds following the geomagnetic storm onset are generated in the polar cap of the thermosphere and penetrate to the stratosphere and troposphere, where the atmospheric response can be observed as a sudden increase of pressure and temperature. Strong eastward winds intensify the zonal circulation in mid-latitudes. Ludmany and Baranyi (2000) compared the atmospheric effects driven by solar irradiance and corpuscular radiation and showed that the high speed plasma streams would lead to the modification of the global atmospheric circulation. Further, Prikryl et al. (2003) studied the response of atmospheric circulation to the high speed solar wind as mediated by auroral electrojet, ionospheric convection and atmospheric gravity waves. Their case study and superposed method analysis of the variations of the high-level clouds which have been shown to be a good representation of mid-latitude cyclones, confirm that gravity waves generated by pulsed ionospheric convection (auroral electrojet) as a result of high speed solar wind induced MHD waves coupling to the magnetosphere–ionosphere system, are transmitted to the lower atmosphere and alter the atmospheric circulation.

Therefore, a step by step schematic scenario of solar activity effects on seismic activity could include the following elements:

- pressure pulses associated with high speed solar wind streams or CME driven shocks compress the magnetosphere,
- the auroral electrojet strengthens,
- the generated atmospheric gravity waves are transmitted downwards,
- westward zonal winds strengthen,
- surface air pressure changes,
- the pressure balance on tectonic plates is disrupted and
- if enough tension is accumulated, an earthquake is triggered.

This is just one possible qualitative mechanism for solar activity influence on earthquakes. The identification of the exact chain of events requires much additional work and is beyond the scope of the present paper.

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