Possible relationship between exogenous parameters and seismicity: Ultra-Low Frequency (ULF) of Magnetic Pulsation, Pc

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Abstract: The physical processes of transferring electromagnetic energy from sun to the earth can be referred as Solar – Terrestrial system. It involves terrestrial atmosphere, the outer part of geomagnetic field, and the solar events, which influence them. To further investigate this coupling mechanism, we propose another exogenous source to be analysed which is cosmic ray. In this study, the investigation on possible relationship between geomagnetic ULF pulsation and seismicity due to exogenous parameters has been focused. Unlike other frequency range, ULF waves can propagate through the crust and reach the earth surface, thus produce reliable precursors to large impending earthquakes. In this analysis, solar activity data were obtained from the Goddard Space Flight Center, NASA via the OMNIWeb Data Explorer and the Space Physics Data Facility. Earthquake events were retrieved from the Advanced National Seismic System (ANSS) database. The variability of horizontal component of the geomagnetic field at two different stations; Ashibetsu (Japan) and Langkawi (Malaysia) extracted from Magnetic Data Acquisition System/Circum-pan Pacific Magnetometer Network (MAGDAS/CPMN) were investigated in order to study correlation between the local earthquake epicenter depth at north Japan and north Sumatera and the geomagnetic ULF pulsations. From the results, the significant correlations between solar wind speed, ULF average amplitude (nT) and earthquake's epicenter depth (km) was observed. Higher ULF amplitude Pc 5 corresponds to the high solar wind speed (km/s) and deeper epicenter depth of localized earthquake.

Keywords: Exogenous parameters; earthquake; geomagnetic data; Ultra-low frequency (ULF); epicenter depth

Introduction:

The extra-terrestrial – terrestrial relationship is a central point in many research directions nowadays and some extra-terrestrial – terrestrial relationships have already been confirmed and have been incorporated into several scientific areas (Kovalyov, M and Kovalyov, S, 2015). Scientific research has also provided some evidence on the relation of solar – magnetospheric activity with earthquakes. Different elements of solar activity have been proposed as triggers of seismic activity: solar and lunar tides (Jakubcova and Pick, 1987), solar proton fluxes (Velinov, 1975), earthward movement of the magnetopause caused by an increased solar wind (SW) dynamic pressure (Makarova and Shirochkov, 1999), high SW speed (Sytinskii, 1989). The contribution of various solar impact processes on earth's lithosphere and their association with the seismic event needs much work. Electromagnetic (EM) waves in the ULF (ultra low frequency) range extracted from ground observations are considered as a promising method to monitor the crustal activity (Yumoto, et al., 2009). In recent years considerable work has been done based on ground and satellite observations to find convincing evidence of EM responses during earthquake events (Gokhberg et al., 1982; Molchanov and Hayakawa, 2008; Hayakawa et al., 1996; Hayakawa and Molchanov, 2002). In general, it has been found that out of the wide range of frequencies from ultra-low frequency (ULF) to high frequency (HF) range (0.001 Hz–30 MHz); the ULF band (0.001–10 Hz) is the only one which can produce reliable precursors to large impending earthquakes.

Dynamic processes in the earthquake preparation zones can produce a current system, which can become local sources for the generation of EM fields in different frequencies including ULF (Molchanov and Hayakawa, 1995 and Hayakawa et al., 1999). The high frequency waves are attenuated so rapidly that they cannot be observed on the earth surface, whereas ULF waves can propagate through the crust and reach the earth surface. Therefore, the probability of earthquake signature manifestations is much higher in the ULF range than in other frequency ranges.

The preference of ULF band over others is based on the fact that skin-depths of ULF waves cover all expected earthquake source depths from approximately 5 to 200 km, depending on wave period and the conductivity in the lithosphere. The penetration depth increases with decreasing underground conductivity. Due to this reason ULF waves (geomagnetic pulsations, Pc 3–5 types) have been successfully used in magneto-telluric methods for remote sensing of the earth's crust conductivity, because any structural change in earthquake regions can lead to a change in the crust resistivity which can affect the behaviour of ground observed ULF fields.

To connect the exogenous parameters to seismicity, we have investigated the possibility of ground magnetic pulsations acting as one of the triggering factors by using magnetic pulsation measurements at Ashibetsu (Japan); for earthquakes monitoring in north Japan and Langkawi (Malaysia); for earthquakes monitoring in north Sumatra.

Methodology:

The concept involves the study of both extra-terrestrial and terrestrial parameters. For this study, we examined the extra-terrestrial parameters including cosmic ray intensity, solar cycles (sunspot numbers) and SW speed. The terrestrial parameters examined are earthquakes at different magnitude and epicenter depth (global and local events), and geomagnetic pulsations.

Exogenous parameters and earthquake data

Cosmic ray intensity data can be obtained from Neutron Monitor Database which is organized by University of Oulu. Sunspot cycle in solar activities is a well-known parameter and often used by space physics researchers to monitor the sun's activities. In this research, the values of sunspot numbers (SSN) from Marshall Space Flight Center, NASA database (http://solarscience.msfc.nasa.gov/) were used to indicate different phases of solar cycle. These phases reflect the activity of the Sun. While the parameters of solar activity data; sunspot number and SW speed were obtained from the Goddard Space Flight Center, NASA via the OMNIWeb Data Explorer and the Space Physics Data Facility.

The global earthquake events with magnitude 4.0 to 9.9 Richter scale from year 1963 to 2010 are extracted from ANSS, hosted by Northern California Earthquake Data Center (http://www.ncedc.org/anss/). The earthquakes are selected based on the depth of epicenter less than 100 km to ensure the possible triggering factors from external sources.

Geomagnetic data

Geomagnetic data are used in this study as a monitoring parameter for solar and seismicity coupling. The data was extracted from MAGDAS/CPMN network constructed by Prof. Yumoto. Two (2) stations involved in this study are Ashibetsu (ASB) station in Japan and Langkawi (LKW) station located in Malaysia. The MAGDAS/CPMN magnetometer is a ring core-type fluxgate magnetometer that measures the three components of the geomagnetic field; Horizontal component (H), Declination component (D), and the Vertical component (Z).

Ultra-Low Frequency (ULF) analysis

The 1-sec resolution data from horizontal component were used to examine the geomagnetic pulsations, Pc 3, Pc 4 and Pc 5 as classified by International Association of Geomagnetism and Aeronomy (IAGA) in Table 1. The raw data from MAGDAS/CPMN stations was first bandpass-filtered before we plotted the dynamic power spectra density to identify the occurrences of ULF at Pc 3, Pc 4 and Pc 5.

The dependence characteristic of skin depth on the ULF period in the lithosphere is tabulated in Table 2 (Yumoto et al., 2009). Based on this table, we can see that EM wave with longer time period is able to propagate deeper into the earth's crust.

TABLE 1. IAGA classification of ULF waves in 1964

		Period (sec)	**Freq (mHz)**
Continuous	Pc 1	0.2-5	200-5000
	Pc 2	5-10	100-200
	Pc 3	10-45	22-100
	Pc 4	45-150	6.7-22
	Pc 5	150-600	1.7-6.7
Irregular	Pi 1	1-40	25-1000
	Pi 2	40-150	6.7-25

TABLE 2. Dependence of skin depth on the wave period of the inducing fields and electric conductivity in the lithosphere (Yumoto et al., 2009)

Skin depth, δ (km)			**Conductivity, σ (S/m)**		
			10^{-1}	10^{-2}	10^{-3}
T (period)	**sec**	10	5.03	15.91	50.32
		45	10.68	33.76	106.76
		150	19.4	61.64	194.92
	min	50	87.18	275.66	871.73
		150	150.99	477.46	1509.88

Results and Discussion:

Relationship between cosmic ray intensity and solar activity

To study the relationship between cosmic ray and solar activity, the cosmic ray intensity, sunspot number and SW speed during the solar cycle 23 and the latest solar cycle 24 are plotted as in Figure 1 a),b) and c). This figure indicates the anti-correlation between cosmic ray cycle and solar cycle. During the ascending and maximum solar cycle, the cosmic ray is descending and at minimum cycle. Furthermore, high SW speed, V_{sw} with the speed more than 500km/s (remarked as in red box in Figure 1 c)) are observed during descending and minimum solar cycle or ascending cosmic ray cycle.

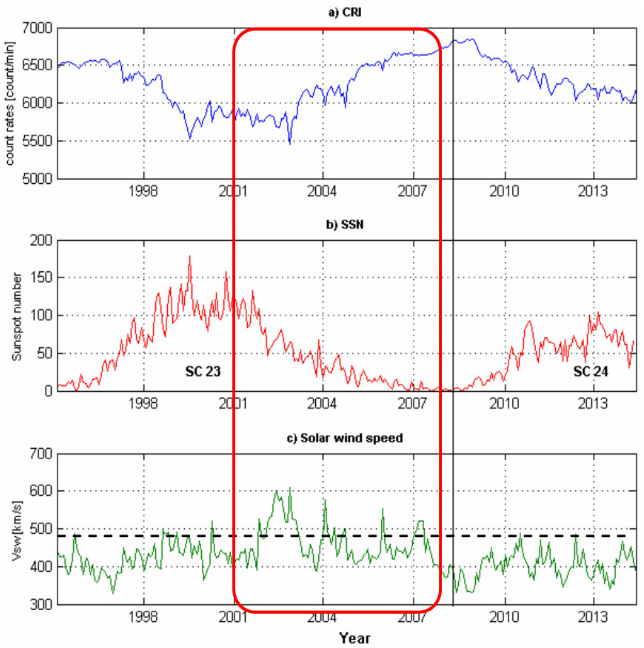

Figure 1: 27-averaged exogenous parameters a) Cosmic ray intensity, b) sunspot number and c) SW speed

This finding highlights that higher tendency of high speed SW occurs during the descending and minimum of solar cycle or ascending cosmic ray cycle. This is supported by the study of Kovalyov, M and Kovalyov, S, (2015) which reveals that there is a possibility that other extra-terrestrial parameter which is cosmic ray could influence the variation of solar activity.

Variation of earthquake occurrence and solar cycle

The percentage of earthquake event occurred at different phases of solar cycle as shown in Figure 2, has been plotted to study the possible relationship between solar cycles (SSN) and earthquakes starting from the lowest earthquake magnitude (mag 4.0) to the highest magnitude (mag 9.0). Four solar cycles are studied from the year 1963 to 2009 which are solar cycles 20 to 23. During this period of observation, we can see earthquakes have higher tendency more than 60% to occur during minimum and descending phases of solar cycle at all magnitude.

Overall, we can see more earthquakes tend to occur around minimum and descending phases of solar cycle especially for greater earthquake magnitudes. This trend confirms the results by Gousheva et al., (2003) and Khain and Khalilov (2007), which show that the earthquake at higher magnitude (M ≥ 7.0) corresponds better to solar activity.

Variation of earthquake epicenter depths with solar cycle

We further examined the previous results by plotting the number of earthquakes with respect to SSN during the same period (solar cycles 20 to 23) as shown in Figure 3 for the case of shallow (< 40 km) earthquakes and Figure 4 for deeper earthquakes (40-100 km). Y-axis on the left panel represents the number of yearly earthquake events and X-axis represents the yearly sunspot number. Y-axis on the right panel shows the total number of earthquake events at each sunspot level which are categorized into 0-20, 20-40, 40-60, etc. ranges of sunspot number. From Figure 3, we can see that the largest number of shallow earthquakes is observed at the lowest level of sunspot number below 20 with ~ 56,000 events in total. The number of earthquakes decreases with increasing SSN until SSN reaches 60. It then stays stable except for an increase between 120 and 140 SSN. The same trend can also be observed with earthquake events at epicenter depth in between 40 to 100 km. The only difference is that the total number of earthquake events is smaller than that of shallow earthquakes.

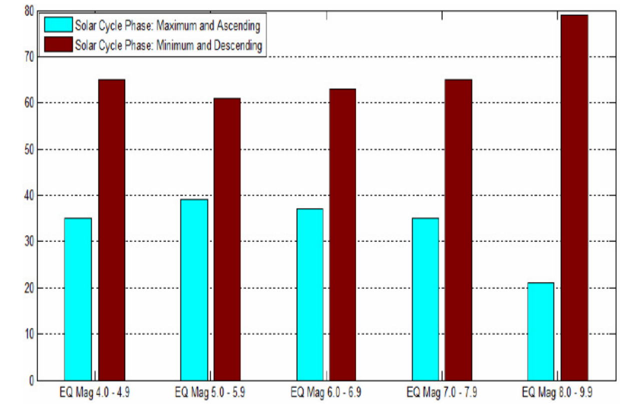

Figure 2: Percentage of earthquakes during different phases of solar cycles 20 to 23

Overall, more earthquakes seem to occur at lower range of SSN. This result confirms the study by Tavares et al. (2011). The field experiments observed by Zeigarnik et al. (2007) shows that the number of shallow earthquakes at epicenter depth between 5-25 km occurred more frequently after the high power EM pulses injected into the earth crust. This shows the possibility of shallow earthquakes to be triggered by external sources. However, more investigations on extra-terrestrial and terrestrial factors are needed to confirm this expectation.

ULF: Relation between earthquake occurrence and epicenter depth (km)

For this study, we have examined the statistics of earthquake occurrences at different epicentre depths for both regions. Figure 5 and Figure 6 show the number of earthquakes at different epicenter depth in north Japan region during the year of 2005 and in north Sumatra region during year the 2010, respectively. We can see most earthquakes in both regions occurred at around 30 to 60 km depth. By assuming the lithosphere conductivity, σ is 10^{-2} S/m from Table 2, Pc 5 range at the period of 150 sec is the best ULF wave to be associated with earthquakes in these regions, as it has a skin depth of 61.64 km which is similar to the epicenter depth.

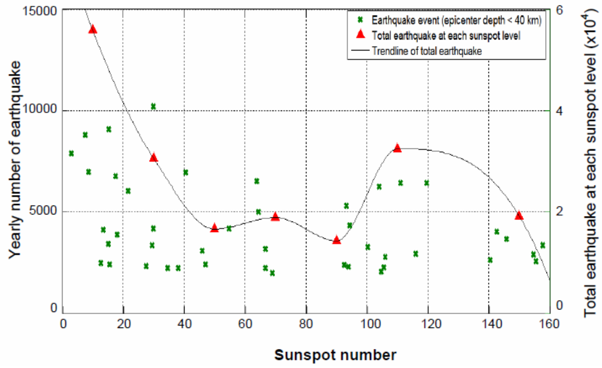

Figure 3: Variation of yearly shallow earthquake event with respect to sunspot number

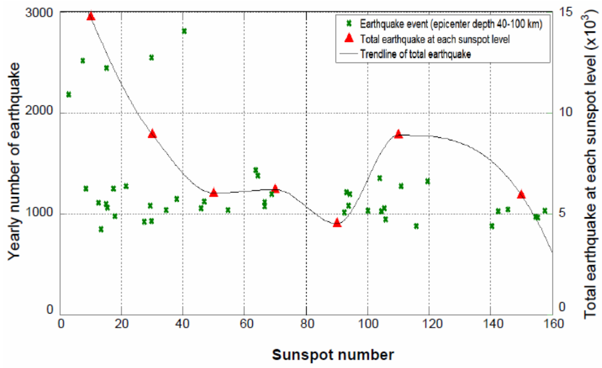

Figure 4: Variation of yearly deep earthquake event with respect to sunspot number

ULF: North Japan region

We have analysed the occurrence of earthquake events within 150 km radius from the MAGDAS Ashibetsu (ASB) station, Japan from 15 August to 15 September 2005. During the period of analysis, 47 earthquake events were recorded. The earthquakes with epicenter depth 60 km or less were selected and compared with the SW speed, V_{sw} and average amplitude of geomagnetic pulsation Pc 5. All of the parameters are plotted hourly throughout the period of observation to precisely monitor the activities of V_{sw}, Pc 5 and the number of earthquakes.

In Figure 7(a), we can see the variation of SW speed with 4-peak trends varies from average speed 400 km/s to 700 km/s. The pattern of solar wind speed can be clearly seen from the plotted trend-line. Figure 7(b) shows the geomagnetic pulsations Pc 5 extracted from ground magnetometer which gives the localized reading of magnetic pulsation in the frequency range of 1.7-6.7 mHz (refer to Table 1 for detail classification of ULF waves). From the plot, we can see clearly the average amplitude of Pc 5 varies between 0 to 2 nano Tesla (nT). The trend-line of Pc 5 shows a good correspondence with that of the SW speed. This confirms the studies by previous researchers that Pc 5 is a good index for SW speed (Baker et al., 2005 and Rae et al., 2005).

Figure 7(c) shows the epicenter depth of earthquakes occurred during the same period. Comparing with Figure 7(b), we can see the number of earthquakes with epicenter depth of ~ 60 km follows

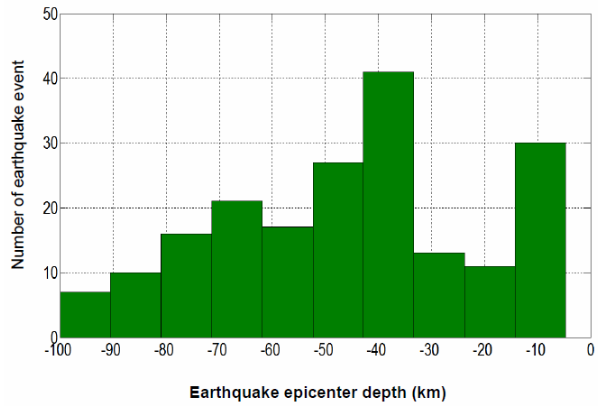

Figure 5: Epicenter epth of North Japan region earthquake for year 2005

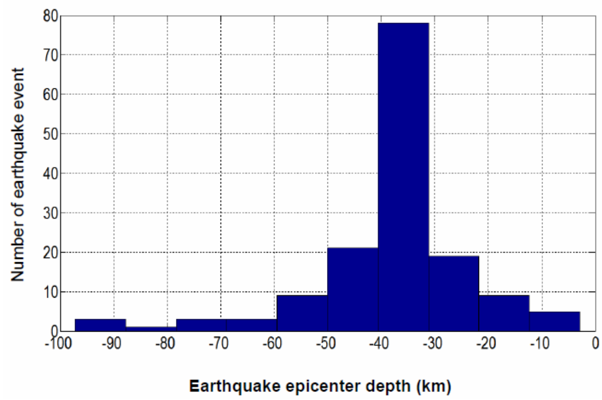

Figure 6: Epicenter depth of North Sumatra region earthquake for year 2010

closely the amplitude of Pc 5. This demonstrates the potential connection between the two.

ULF: North Sumatra region

For this region, we have done a similar analysis to the north Japan region but in a different time period to see the correspondence of geomagnetic pulsation Pc 5 and earthquake occurrences in Sumatra region. The observation of SW speed, geomagnetic pulsation Pc 5 and earthquake event shown in Figure 8 (a), (b) and (c) respectively was done during a 1-month period from 12 March to 11 April 2010. The geomagnetic pulsation Pc 5 was extracted from observations at MAGDAS Langkawi (LKW) station, Malaysia.

By referring to Figure 8 (a), at first 100-hour of observation, the SW speed was 500 km/s before decreasing and increasing in the next 200-hour period. The SW speed later decreases smoothly and started to increase again in the 300-hour period and reached its peak at the end of 500-hour period with speed at around 780 km/s. This SW speed variation corresponds well with that of the geomagnetic pulsation Pc 5 as shown in Figure 8 (b). Throughout the observation period, the average amplitude of geomagnetic pulsation Pc 5 is around 2 nT. However, several events

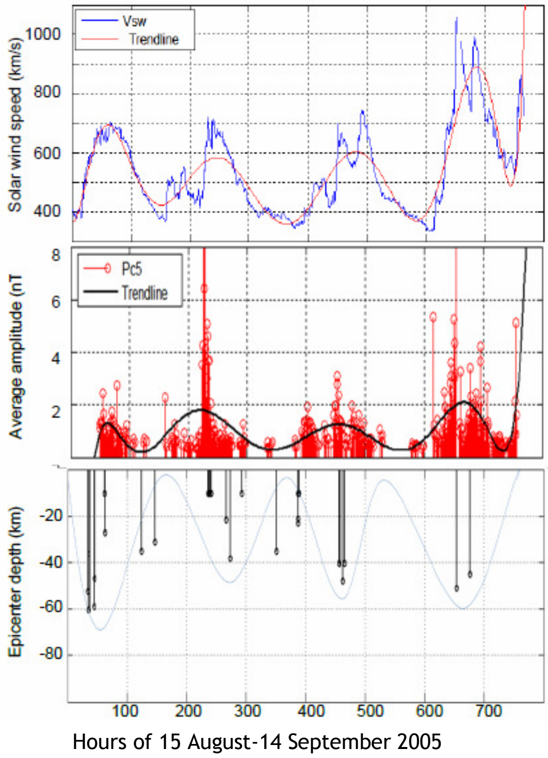

Figure 7: Variation of (a) SW speed, (b) amplitude of Pc 5 and (c) epicenter depth earthquake events from 15 August to 14 September 2005 for North Japan region.

of high Pc 5 amplitude at more than 2 nT were observed around 200-hour, the same period of SW speed enhancement. The maximum value of average Pc 5 amplitude with value around 7 nT was recorded at the end of 500-hour period, also at the same time we observed the maximum SW speed. The trend-lines for both plots show the similar pattern between them.

The epicenter depth of earthquake events which occurred around this region was plotted in Figure 8 (c). If we compare it with the average amplitude of Pc 5, the number of earthquake events with epicenter depth of ~ 60 km tends to occur more during higher average amplitude of Pc 5. Two periods with the enhancement of earthquake events are during the first 200 hour where the average amplitude of Pc 5 was high and during 600-hour period, around 50 hours after the maximum average amplitude of Pc 5.

The three (3) observed parameters have a good correspondence in tendency. It can be summarized that during the enhancement of SW speed, average amplitude of geomagnetic pulsation Pc 5 tends to increase as well and more number of earthquake events with epicenter depth around 60 km occur.

The correlation of earthquakes with geomagnetic pulsation Pc 5 for both regions; north Japan and north Sumatra can be considered as promising, in agreement with several previous studies. The observations of geomagnetic pulsations or ULF anomalies related with earthquake events have been reported in various, geologically distinct regions of the

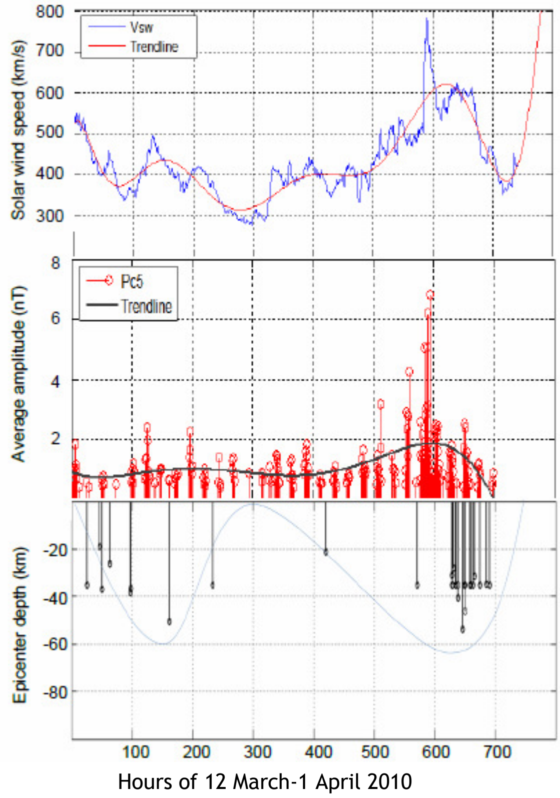

Figure 8: Variation of (a) SW speed, (b) amplitude of Pc 5 and (c) epicenter depth earthquake events from 12 March to 11 April 2010 for North Sumatra, Indonesia region.

world (Fraser-Smith et al., 1990; Molchanov et al. 1992; Kopytenko et al. 1993; Hayakawa et al. 1996).

On the other hand, the studies to relate SW speed and pulsations have been done and established by previous researchers. For example, Saito (1964) and Singer et al. (1977) showed that pulsation activity correlates well with the SW speed. Later, several authors (Greenstadt et al., 1977; Wolfe, 1980; Wolfe et al. 1985) showed that both the cone angle (the angle between the IMF orientation and the Earth-Sun line) and the SW speed control the occurrence and the amplitude of ground pulsations in the Pc 3 and Pc 4 range. Greenstadt et al. (1979) observed positive correlations of magnetic pulsations Pc 3, Pc 4 and Pc 5 at Calgari and Leduc stations with SW speed.

The previous analysis demonstrates the possibility of geomagnetic pulsations as one of the parameter connecting solar activity and seismicity.

Conclusion:

In recent years the study of solar activity and its effects on the Earth's tectonic activity has dramatically increased. These works and results have indicated the Sun's pervasive influence on many geophysical activities of the Earth including earthquakes, volcanic eruptions and global warming. This work examines the relation between solar activity and seismicity study by considering observations on global and local earthquake events. In our attempts to explain the physical mechanism of solar activity and seismicity, we are focussing on geomagnetic pulsations extracted from the ground magnetometer.

In this study, we consider geomagnetic pulsations as one of the possible parameter to connect the solar activity with seismicity. Since our analysis only focus on the response of geomagnetic pulsation Pc 5, therefore, to this stage, we could only conclude that it is possible to consider geomagnetic pulsation Pc 5 as monitoring parameter for earthquake event in a scope of solar and seismicity coupling. The consideration on different range of geomagnetic pulsations as monitoring parameters definitely needs further analysis on the various earthquake events with different epicenter depth at the diverse geological seismic regions.

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References

Baker, N. D.: 2005, Lecture Notes in Physics. 656, 993.

Fraser-Smith, A. C., Bernardi, A., McGill, P. R., Ladd, M. E., Helliwell, R. A. and Villard, O. G Jr.: 1990, Geophysical Research Letters. 17, 1465.

Gousheva, M. N., Georgieva, K. Y., Kirov, B. B., Atanasov, D.: 2003, in International Conference Proceedings of Recent Advances in Space Technologies, (RAST '03), On the relation between solar activity and seismicity, p. 236.

Greenstadt, E. W. and Olson, J. V.: 1977, Journal of Geophysical Research. 82, 4991.

Greenstadt, E. W., Olson, J. V., Loewen, P. D., Singer, H. J. and Russell C. T.: 1979, Journal of Geophysical Research. 84, 6694.

Hayakawa, M., Molchanov, O. A., Ondoh, T., and Kawai, E.: 2002, J. Comm. Res. Lab., Tokyo. 43, 169.

Hayakawa, M. and Molchanov, O. A. Editors.: 2002, TERRAPUB, 477.

Hayakawa, M., Ito, T. and Smirnova, N.: 1999, Geophysical Research Letter. 26, 2797.

Jakubcova, I., and Pick, M.: 1987, Annals Geophysics. 5(B), 135.

Khain, V. E and Khalilov, E. N.: 2007, in Transactions of the International Academy of Science H&E, p. 217.

Kopytenko, Y.A., Matiashvili, T.G., Voronov, P. M., Kopytenko, E. A. and Molchanov, O. A..: 1993, Physics of Earth and Planetary Interiors. 77, 85.

Kovalyov, M and Kovalyov, S.: 2015, arXiv preprint arXiv: 1403.5728, 1.

Molchanov, O. A., Yu. A. Kopytenko, Voronov, P. M., Kopytenko, E. A., Matiashvili, T. G., Fraser-Smith, A. C. and Bernardi, A.: 1992, Geophysical Research Letters. 19, 1495.

Molchanov, O. A. and Hayakawa, M.: 1995, Geophysical Research Letters. 22, 3091.

Molchanov, O. A., and Hayakawa.: 2008, TERRAPUB, Tokyo, 189.

Rae, I. J., Donovan, E. F., Mann, I. R., Fenrich, F. R., Watt, C. E. J., Milling, D. K., Lester, M., Lavraud, B., Wild, J. A., Singer, H. J., Rème, H., and Balogh.: 2005, Journal of Geophysical Research. 11.

Saito, T.: 1964, Report on Ionospheric Space Research, Japan. 18, 260.

Singer, H. J., Russell, C. T., Kivelson, M. G., Greenstadt, E. W., and Olson, J. V.: 1977, Research Letters. 4, 377.

Sytinskii, A. D.: 1989, Fizika Zemlli. 2, 13.

Wolfe, A.,.: 1980, Journal of Geophysical Research. 85, 5977.

Wolfe, A., Meloni, A., Lanzerotti, L. J., and MacLennan, C. G.: 1985, Journal of Geophysical Research. 90, 5117.

Yumoto, K., Ikemoto, S., Cardinal, M. G., Hayakawa, M., Hattori, K., Liu, J. Y., Saroso, S., Ruhimat, M., Husni, M., Widarto, D., Ramos, E., McNamara, D., Otadoy, R.E., Yumul, G., Ebora, R., and Servando, N.: 2009, Physics and Chemistry of the Earth, 360.

Zeigarnik, V. A., Novikov, V. A., Avagimov, A. A., Tarasov, N. T. and Bogomolo, L. M.: 2007, in 2nd International Conference on Urban Disaster Reduction, Discharge of Tectonic Stress in the Earth Crust by High-power Electric Pulses for Earthquake hazard Mitigation.