

Solar Activity and Seismicity

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Solar Activity and Seismicity

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九州大学

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Solar Activity and Seismicity

A DISSERTATION

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BY

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Abstract

Solar activity plays an important role in regulating the electromagnetic coupling between the Sun and the Earth. Therefore, investigations on different elements of solar activity and their possible effects on seismic activity are important. This research investigates the possible relationship between different solar parameters and seismic activities.

In the first part of this study, we have analyzed long term trend of global and local earthquake occurrence and its energy with sunspot numbers. The observation period covers 4 most recent solar cycles 20-23 from year 1963-2008. In the second part, we have analyzed the earthquake events with respect to high speed solar wind (HSSW), solar wind dynamic pressure (P_{dyn}) and solar wind input energy ($\mathcal{E}$). In the first part of analysis shows that both local and global seismic activities tend to occur more frequently in the descending phase of the solar cycles. This trend is similar to those detected in HSSW, P_{dyn} and solar wind input energy.

To connect the solar wind and the seismic activity, we examine two possibilities. The first is the ground magnetic pulsations as one of the connecting agent. We analyzed ground magnetic pulsations at different ranges of ultra low frequency, e.g. Pc3 (22-100 mHz), Pc4 (6.7-22 mHz) and Pc5 (1.7-6.7 mHz) with the occurrence of localized earthquake events. This analysis focuses at 2 different seismic regions; Japan and Sumatra/ Indonesia. Our results show that Pc5 range pulsation is the most likely connection between the solar wind and seismic activity. The second possibility we examined is the Lorentz force produced by the underground current induced by the ionospheric Sq current system. Our analysis shows the Sq current may provide enough energy for earthquake activities.

The overall analysis shows earthquakes of all magnitude tend to occur more frequently during descending solar cycle, when the solar wind parameters (solar wind speed, input energy and dynamic pressure) are high. However, one solar wind event does not trigger one earthquake. Geomagnetic pulsations and Lorentz force produced by induced currents can be possible connecting agents between the solar wind and the seismic activity.

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Chapter 1

Introduction

1.1 Concept of Solar Seismicity Coupling

The sun is the main source of energy to the solar system, and it plays a major role in affecting the ionosphere, atmosphere and the earth's surface. The Sun-Earth relationship is a central point in many research directions nowadays and some Sun-Earth relationships have already been confirmed and have been incorporated into several scientific areas. In particular, the space science community has concentrated its interest on so-called "space weather" in order to predict geomagnetic and ionospheric disturbances, which have a significant impact on electrical power systems, telecommunications, oil pipelines, spacecraft and aircraft electronics, astronauts safety, etc. [Baker, 2005; Marhavilas, 2008; Lanzerotti, 2010]. Scientific research has also provided some evidence on the relation of solar – magnetospheric activity with earthquakes.

Figure 1 shows the concept of solar – seismicity coupling. The concept involves the study of both extraterrestrial and terrestrial parameters. For this study, we examined the extraterrestrial parameters includes solar cycles (sunspot numbers), solar wind speed (SW speed), solar wind dynamic pressure (SW dynamic pressure) and solar wind input energy (SW input energy). The terrestrial parameters examined are ionospheric current, earthquake at different magnitude and epicenter depth (global and local events), and geomagnetic

pulsations. The details of the examined parameters will be explained in the following chapters.

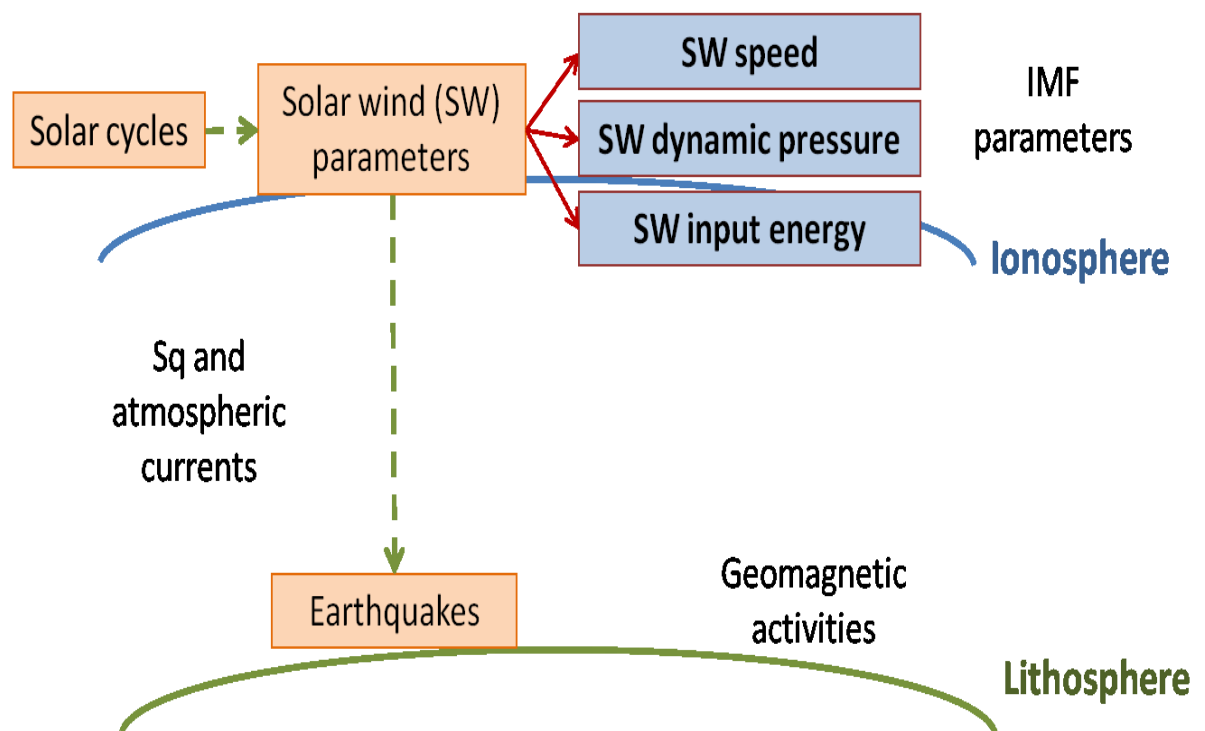


Figure 1: General concept of solar – seismicity coupling

1.2 Solar activities associated with earthquakes

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. Theoretically, this coupling mechanism starts from the sun as the main source of energy to the solar system and plays a significant role in affecting the interplanetary space, magnetosphere, ionosphere, neutral ionosphere and biosphere.

The main focus addressed in this study is the possible relationship between solar activity and seismicity. Several authors [Gousheva et al., 2003, Odintsov et. al, 2006, Khain and Khalilov, 2008] reported that although many researchers have studied the influence of extraterrestrial factors in seismicity by demonstrating some evidences and statistical analysis, the problem remains ambiguous. Recently, there is an increasing evidence for an influence of solar activity upon seismic activities. For instance, Khain and Khalilov [2008] presented statistical results that in both the spectra of earthquakes with magnitude, $M \geq 7$ Richter scale and sunspot numbers, the main harmonic was found at $T \approx 10\text{-}11$ years. The authors suggested a long-term forecast for seismic activity until 2018 based on its high correlation with solar activity. Odintsov et al., [2006] determined that the maximum of seismic energy released from earthquake is observed during the declining phase of solar cycle and it lags 2 years behind the year of solar maximum.

Other than that, Gousheva et al., [2003] has performed a statistical study and they found two maxima in the global yearly number of earthquakes in the 11-year sunspot cycle, one coinciding with the solar cycle maximum, and the other on the

descending phase of the solar cycle. In agreement with these results, S. Odinstov et al. [2006] confirmed that the maximum earthquakes occurrence directly correlates with a sudden increase in the solar wind velocity.

1.3 Motivation and objective of this study

1.3.1 Motivation

Even though several authors have demonstrated possible solar cycle relationship with earthquake events, very few authors have attempted to investigate on the causal effect of solar wind parameters and earthquakes.

Tsurutani and Gonzalez, [1997] reported that, during the period of high electromagnetic energy input, the amplitude of Sq current in the ionosphere will also be enhanced. Through induction process, the Sq current variation in the ionosphere will induce underground current [Matsushita, 1968]. Therefore, the increase of Sq current in the ionosphere will also increase the amount of induced underground current.

Furthermore, Zeigarnik et al., [2007] reported a probable triggering effect of anthropogenic impulsive electrical signals on seismicity. Analyzing variations of the number of earthquakes in Kyrgyzstan associated with electrical signals radiated by an MHD generator, they inferred that the number of earthquakes tends to increase 2 to 6 days after the electrical signal passage.

This is similar to the case when we consider the source of high electromagnetic energy from the solar wind event (eg: geomagnetic storm). By investigating solar wind parameters, it could be possible to examine the relationship between solar activity and seismicity.

1.3.2 Objective

As we have seen before, to date, previous researchers have done the investigations on relationship of:

- Global EQ and solar cycle (SC 18-19) [Simpson, 1967; Belov et al., 2009]
- EQ and High speed solar wind during SC 21-22 [Odintsov et al., 2006]
- Global geomagnetic activities & Sq current [Duma et al., 2002; Gousheva et al., 2003]

In order to investigate the possible solar – seismicity coupling, we have to:

1. Re-examine the relationship between global earthquake and high speed solar wind with longer time period (4 solar cycles; SC 20-23).
2. Examine the relationship of local earthquake and its released energy at longer time period (4 solar cycles).
3. Examine possible relationship between EQ and solar wind dynamic pressure, and solar wind input energy.
4. Examine geomagnetic pulsations_as connecting parameters between solar and EQ events.

1.3.3 Outline

The current work aims to examine the possible connection between solar activity and earthquakes. The study is divided into five chapters; begins with this chapter as introduction part to solar – seismicity coupling. 2nd chapter will explain the methodology used in the study, then followed by results and analysis in the Chapter 3. The possible physical mechanism connecting solar activity and seismicity will be discussed in Chapter 4, and then the summary of the study will be in the last chapter.

Chapter 2

Data

Methods of data analysis – In this study, we are investigating the possible effect of solar activity on seismicity. Therefore, a comprehensive analysis for possible correlation of solar activity and seismicity requires a large database to clearly explain the relationship between them.

2.1 Earthquake data

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 are from external sources.

The energy released in earthquakes is calculated based on Kanamori seismic energy method [Kanamori, 1983]:

$$\text{Log } E = 1.5M + 4.7 \quad (1)$$

Where E is the earthquake energy expressed in Joule unit and M is the earthquake magnitude.

2.2 Solar cycle data

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 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. An active Sun occurred during maximum while minimum indicates low activity period of the sun.

2.3 Solar wind data

Solar wind is a highly ionized gas originated from the sun. It is one of the most prominent features of the Sun and acts as a medium for the solar control of the earth. Lots of space missions were and still are dedicated to observe its composition, velocity, density and temperature, inside and, outside of the terrestrial magnetosphere (WIND, ACE, Ulysses, SOHO). All the parameters of solar wind data for this study were obtained from the Goddard Space Flight Center, NASA via the OMNIWeb Data Explorer and the Space Physics Data Facility.

2.3.1 Solar wind speed

Solar wind plasma consists of electrons, protons, helium and heavier nuclei, which are carrying along them the solar magnetic field resulting into an interplanetary magnetic field (IMF). The average velocity of the solar wind plasma is 350 km/s with minimum of about 200 km/s and a maximum over 1000 km/s.

In this study, a high speed solar wind (HSSW) is characterized by four factors [Mavromichalaki and Vassilaki, 1998]; considerable enhancement in plasma stream

speed ($\Delta V_{sw} \geq 100$ km/s), higher temperature (T in K), a high variation of proton density (N in cm^{-3}) and higher magnitude of IMF (B in nT).

Solar wind from the sun can be categorized into slow and fast solar winds which have different origins in the solar coronal [Lyatsky et al., 2007 and Gupta and Badruddin, 2010]. During HSSW originated from coronal holes (CH-HSSW), the plasma speed increases relatively slowly to reach its maximum, with similar pattern in temperature, while the proton density and magnitude of IMF reaches its peak before the speed maximum. During HSSW from coronal mass ejection (CME-HSSW), the speed increases faster and rises to peak value simultaneously with proton density and magnitude of IMF while its temperature becomes lower after the initial rise during the shock. Figure 2 shows the typical CME-HSSW and CH-HSSW.

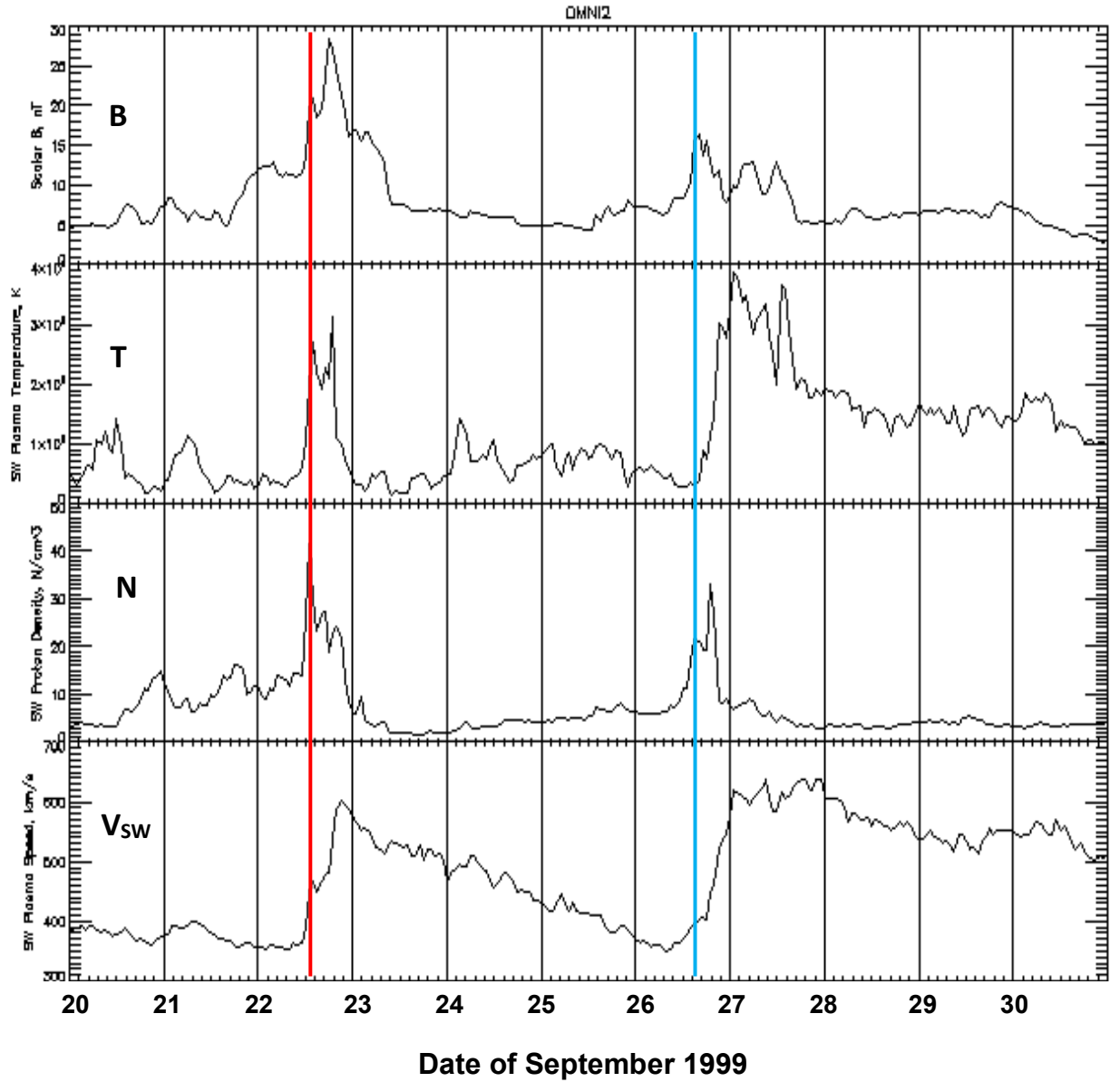


Figure 2: Typical CME-HSSW (red-line detected on 22 September 1999) and CH-HSSW (blue-line detected on 27 September 1999). The observation period is from 20 September to 30 September 1999.

2.3.2 Solar wind dynamic pressure

In space weather study, the effects of solar wind to the earth system are very significant. The enhancement of dynamic pressure caused by solar wind flow; called solar wind dynamic pressure (SW P_{dyn}) has been widely discussed by previous researchers [Russell et al., 1994; Lyons et al., 2000; Zesta et al., 2000; Boudouridis et al., 2003 and Lee et al., 2004 to name a few]. The solar wind dynamic pressure can be calculated from formula (2):

$$\text{SW P}_{\text{dyn}} = 1.6726 * \text{exp-6} * N * V_{\text{sw}}^2 \quad [\text{nPa}] \quad (2)$$

Where: N = Proton density and V_{sw} = Solar wind speed

2.3.3 Solar wind input energy

The penetration of solar wind energy from the magnetosphere to the ionosphere and further transfers to lower atmosphere and lithosphere is an important process in solar physics. It has been explained empirically by several researchers [Dungey, 1961; Axford and Hines, 1961 and Akasofu, 1981]. Solar wind input energy can be calculated using formula (3) [Akasofu, 1981]:

$$\text{Epsilon } (\epsilon) = V_{\text{sw}} * B^2 * F(\theta) * l_o^2 \quad [\text{Watt or Erg/s}] \quad (3)$$

Where:

V_{sw} = solar wind speed,

B = IMF magnetic field,

l_o = 7 Earth radii and

$F(\theta)$ = function of the angle θ (B_y/B_z).

$F(\theta)$ denotes a function of the angle θ , the polar angle of the IMF vector, projected onto the Y-Z plane, namely:

$$\theta = \tan^{-1} \text{abs}(B_y/B_z) \text{ for } B_z > 0$$

$$\theta = 180^\circ - \tan^{-1} \text{abs}(B_y/B_z) \text{ for } B_z < 0$$

2.4 MAGDAS instrumentation and geomagnetic field variation

International Center for Space Weather Science and Education, ICSWSE (the new name for Space Environment Research Center, SERC), Kyushu University, Japan has introduced a real-time Magnetic Data Acquisition System of Circum-pacific Magnetometer Network, i.e. MAGDAS/CPMN for space weather study and application, which was deployed for the International Heliophysical Year (IHY; 2007-2009) [Yumoto et al., 1996]. By using this system, ICSWSE conducted real-time monitoring and modelling of (1) global 3-dimensional current system, (2) plasma mass density, and (3) penetrating process of polar electric fields into the equatorial ionosphere, in order to understand the Sun-Earth coupling system and the electromagnetic and plasma environment changes [Yumoto, 2009]. To date, MAGDAS/CPMN consists of three unique chains of magnetic observatories; most magnetometers were densely installed at 210° magnetic meridian, on African longitude-sector and the other one is along the magnetic equator (with total of 71 stations worldwide), as shown in Figure 3.

From the magnetometer, we can extract the ambient magnetic field, expressed by H (Geomagnetic Northward), D (Geomagnetic Eastward) and Z (Vertical Downward) components.

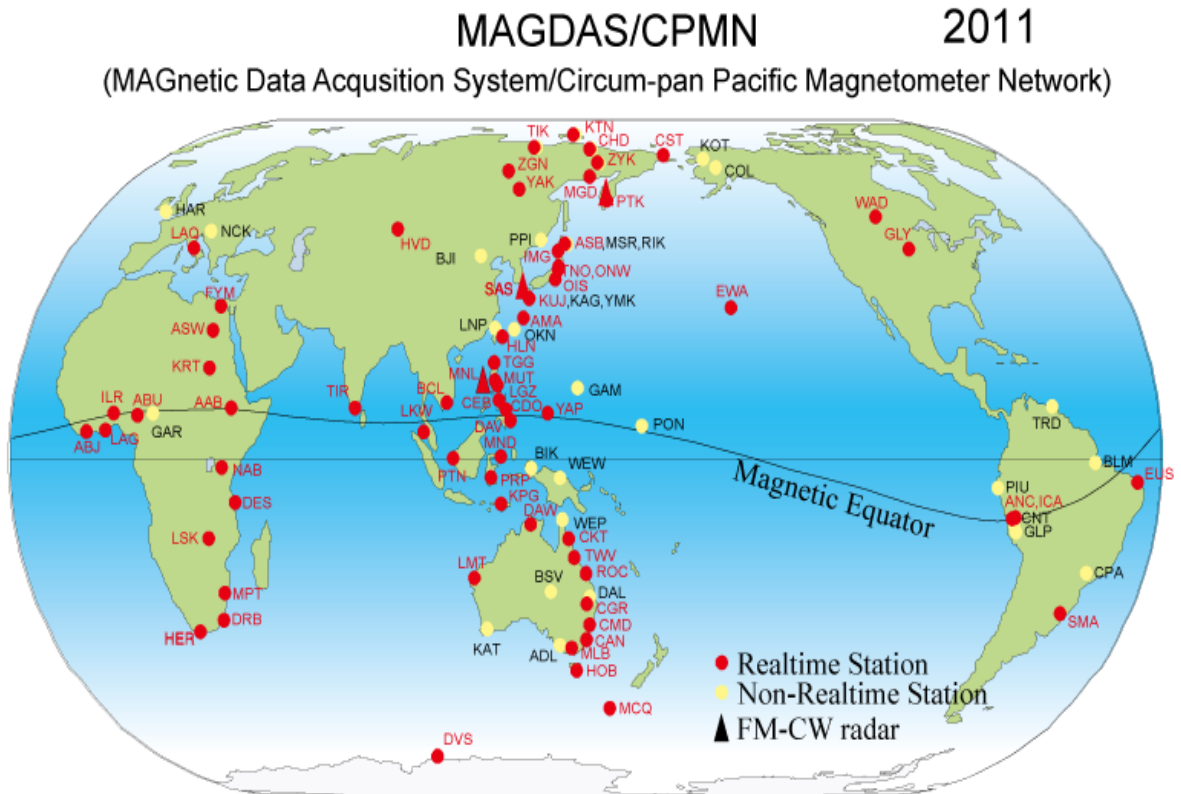


Figure 3: MAGDAS/CPMN (MAGnetic Data Acquisition System/Circum-pan Pacific Magnetometer Network) system of the ICSWSE, Kyushu University.

2.4.1 Geomagnetic data

Geomagnetic data is 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 at 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) as shown in Figure 4 [Campbell, 2003].

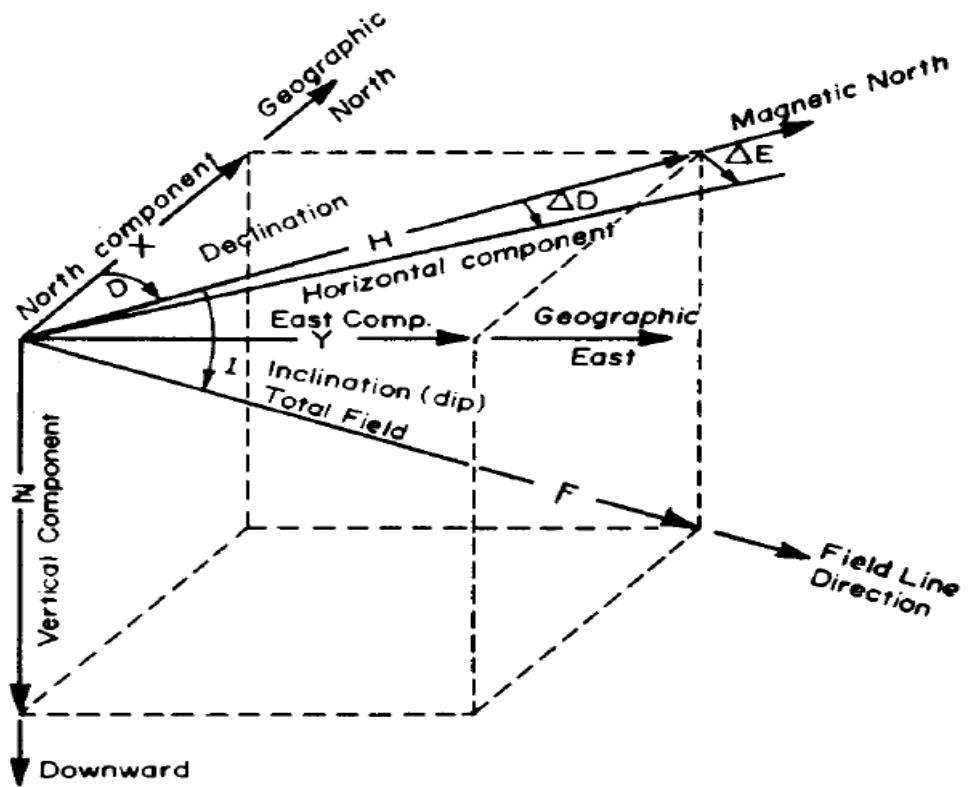


Figure 4: The geomagnetic field components; [F] Total intensity of the geomagnetic field, Horizontal component (H), Declination component (D), and the Vertical component (Z).

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 ultra low frequency (ULF) at Pc 3, Pc 4 and Pc 5.

Table 1: IAGA classification of ULF waves in 1964.

CONTINUOUS						IRREGULAR	
	Pc 1	Pc 2	Pc 3	Pc 4	Pc 5	Pi 1	Pi 2
Period (sec)	0.2-5	5-10	10-45	45-150	150-600	1-40	40-150
Frequency (mHz)	200-5000	100-200	22-100	6.7-22	1.7-6.7	25-1000	6.7-25

Chapter 3

Results

3.1 Variation of Earthquake Occurrence with Solar Cycle (SC)

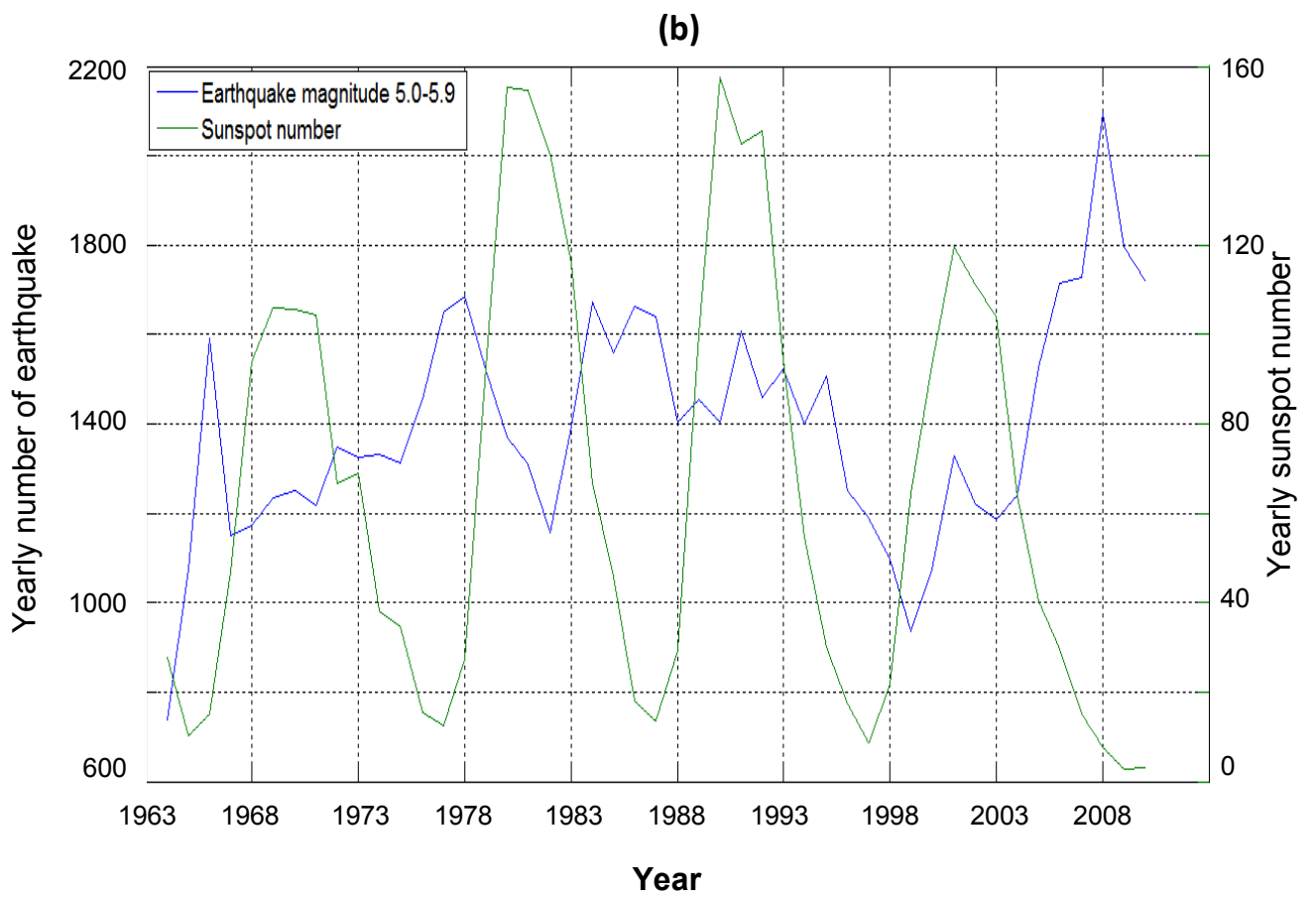
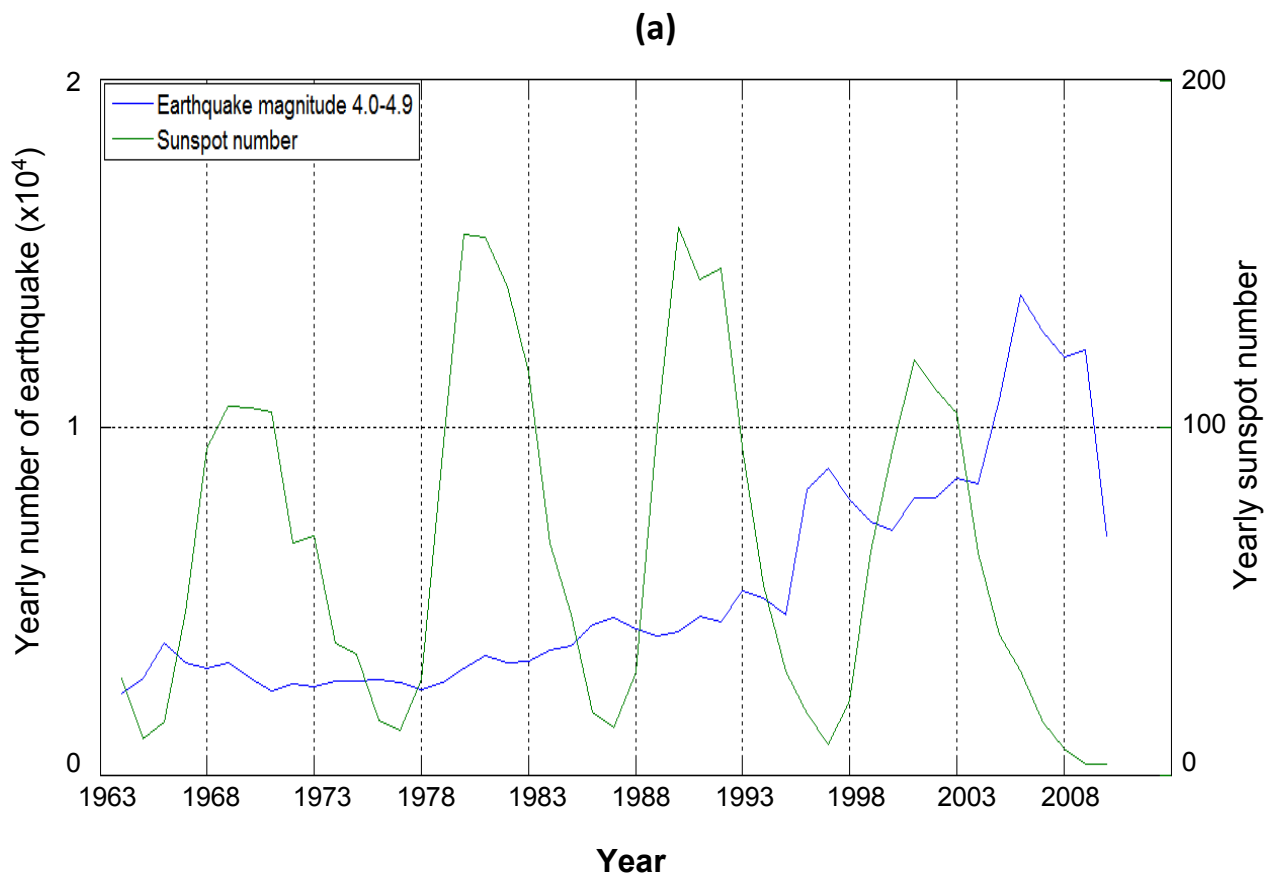
In order to examine the possible relationship between solar cycles (and sunspot numbers) with earthquakes, we have plotted the superposition of both earthquake events and solar cycle for the period of solar cycle (SC) 20 to 23, from year 1963 to 2009 as in Figure 5(a) to (e) starts from the lowest earthquake magnitude to the highest magnitude respectively. The green line is the value of yearly sunspot number and the blue line is the yearly value of earthquake number. We are filtering out the earthquakes with surface in depth more than 100 km since the external factors of earthquakes tend to influence earthquake at shallow or moderate epicenter depth [Sasorova, and Levin, 2007].

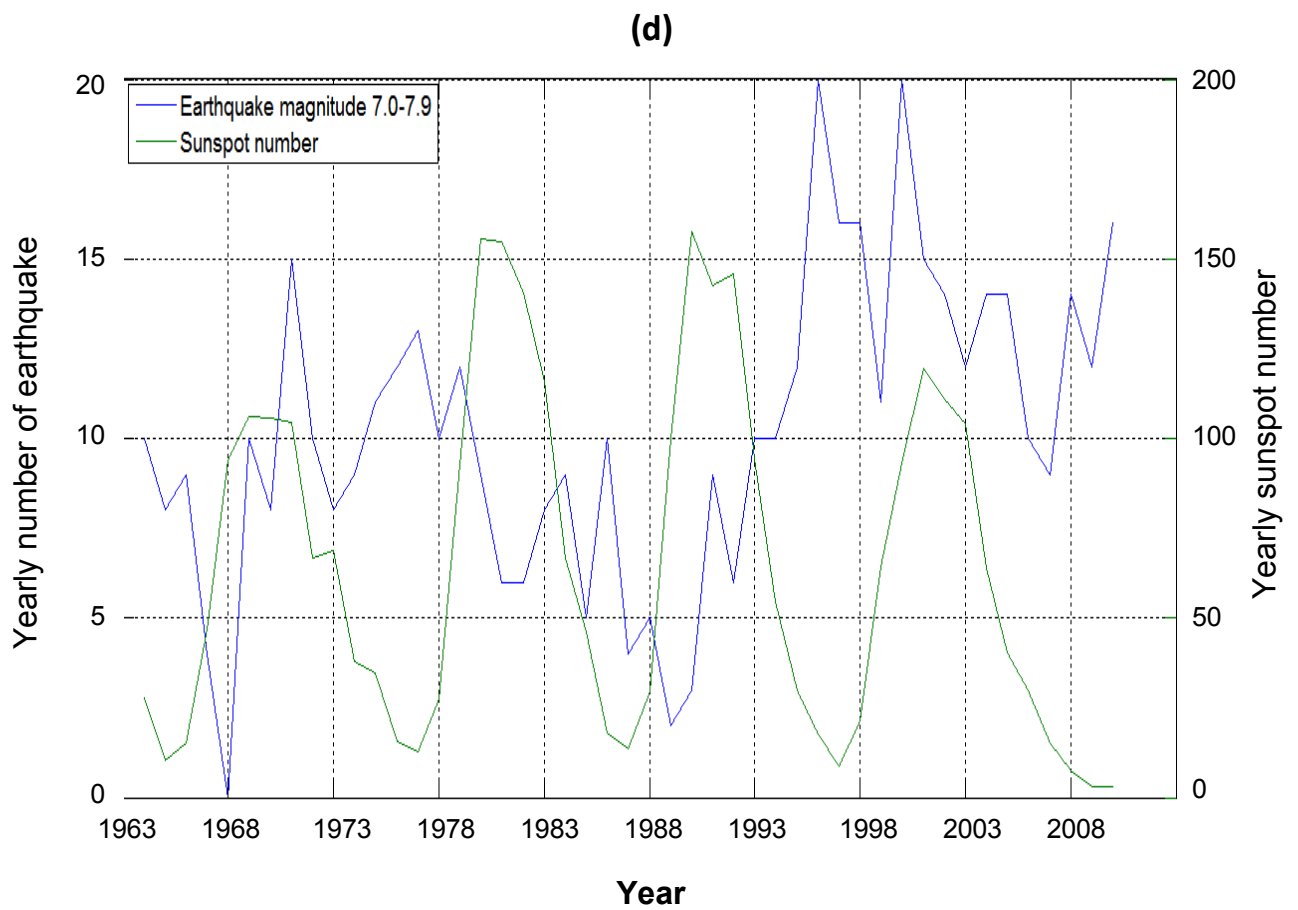
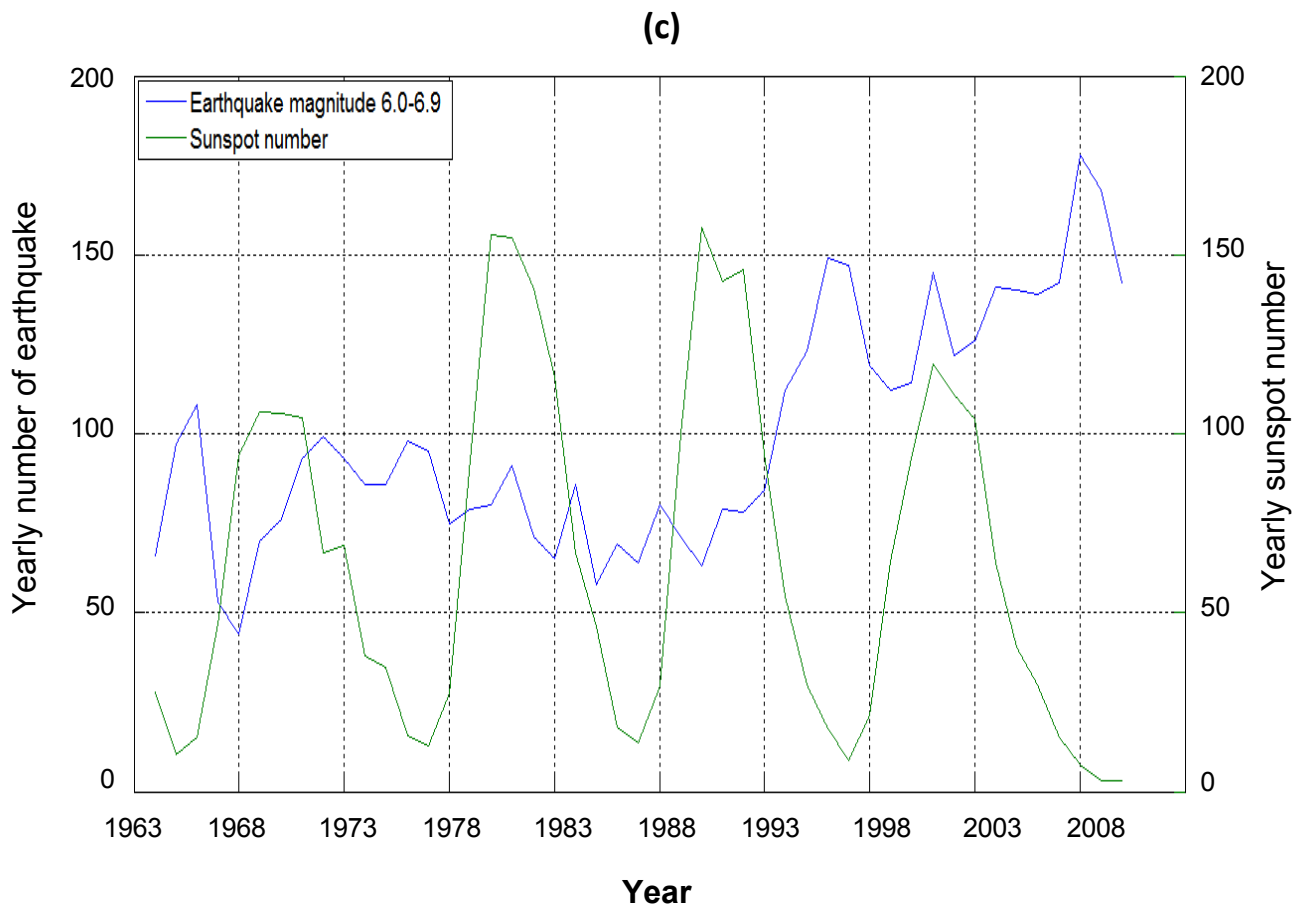
For earthquake magnitude 4.0 to 4.9 Richter scale as shown in Figure 5(a), the total number of earthquakes recorded is 250,661 events. The comparison of earthquake number with solar cycle shows the number of earthquakes is higher during descending and minimum phases of solar cycles mainly during solar cycles 21 to 23. For earthquake at magnitude 5.0 to 5.9 Richter scale as shown in Figure 5(b), we can see several distinctive peaks of earthquake numbers during descending and minimum phases of solar cycle 20 to 23. Total examined earthquake events during this period are 65,694 events.

Figure 5(c) shows the occurrence of earthquakes at magnitude 6.0 to 6.0 Richter scale with total 4676 events. The trend of earthquake occurrence shows an abrupt increase of around 50% started during the descending phase of solar cycle 22.

Higher number of earthquake also appears during the descending period of solar cycle 20, 22 and 23. The total number of earthquake examined at magnitude 7.0 to 7.9 is 476 events as shown in figure 5(d). During the descending and minimum phases of solar cycles; mainly solar cycle 20, 22 and 23, the number of earthquake tend to occur more as compare to other phases. For the highest earthquake magnitude 8.0 to 9.9 as shown in Figure 5(e), earthquakes show the tendency to occur during the descending and minimum phases of solar cycle, mainly during solar cycles 21, 22 and 23. The number of earthquake for this magnitude is higher during the last two solar cycles 22 and 23.

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 [2008] which show the earthquake at higher magnitude ($M \geq 7.0$) corresponds better with solar activity.





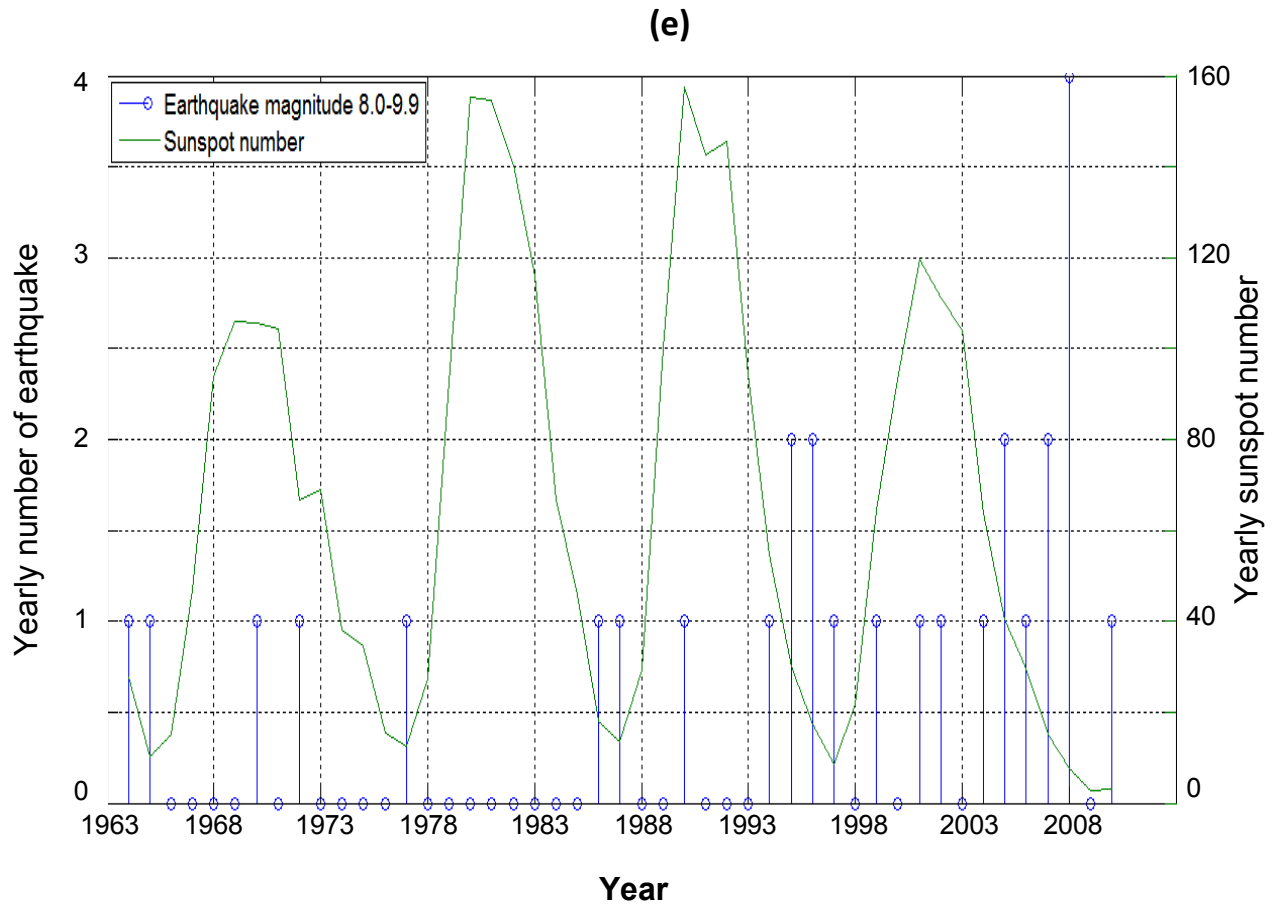


Figure 5: Superposition of sunspot number (Solar Cycle 20 – 23) and Earthquakes;
(a) EQ magnitude 4.0 – 4.9, (b) EQ magnitude 5.0 – 5.9, (c) EQ magnitude 6.0 – 6.9,
(d) EQ magnitude 7.0 – 7.9 and (e) EQ magnitude 8.0 – 9.9

The sunspot numbers and earthquake events at different magnitudes were further analyzed by examining the percentage of earthquake event occurred at different phases of solar cycle as shown in Figure 6. 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.

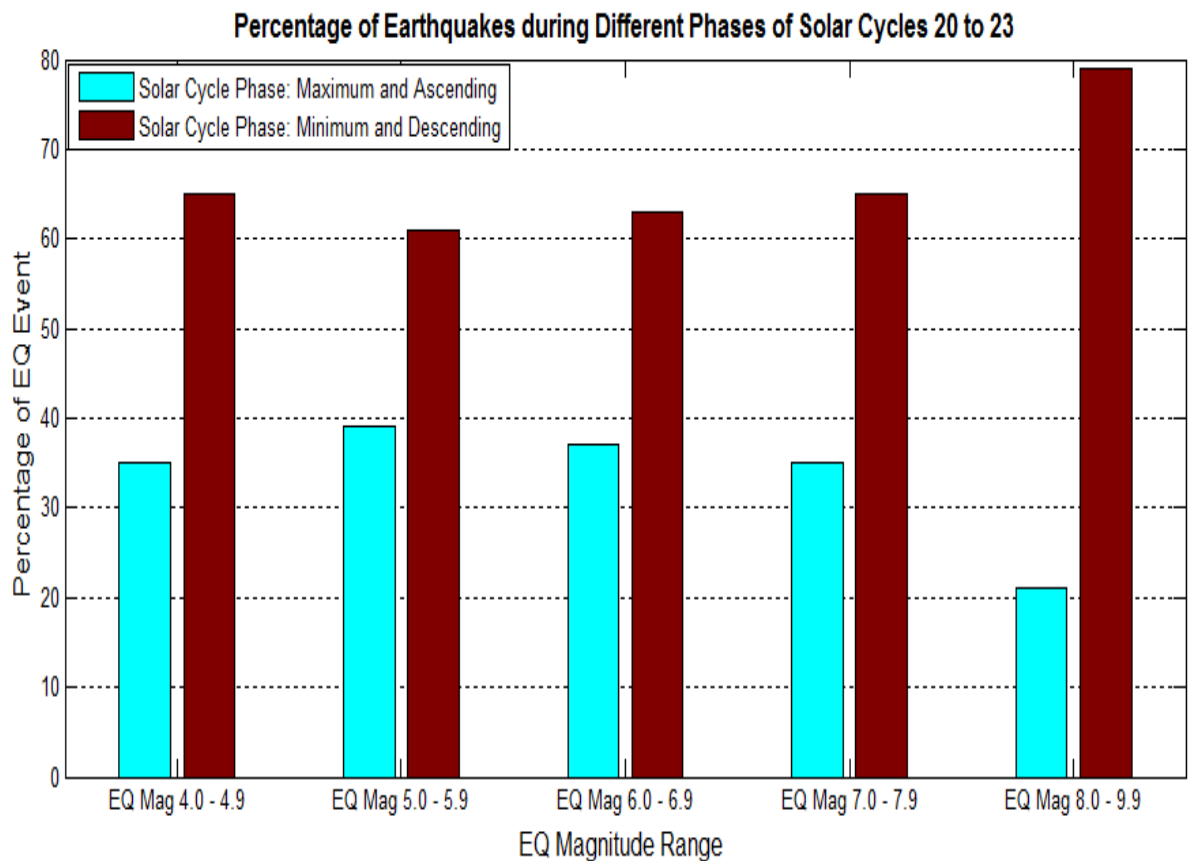


Figure 6: Percentage of Earthquakes during Solar Cycles 20 to 23

3.2 Variation of earthquake epicenter depths with solar cycles

The earthquake epicenter depth is the point under the earth's surface, where the fault begins to rupture and cause earthquake events. This is an important parameter for any earthquake event since the maximum magnitude of earthquakes is decreasing for deeper epicenter depth [Kagan, 1991]. In the recent study by Tavares et al., [2011], they have pointed out that the highest correlation of sun activity and earthquake is observed for shallow earthquake by analyzing the earthquake depth 7 to 35 km. However, there is no comparison has been made for deeper depth earthquake events.

In this study, we have examined the occurrences of earthquakes from wider range of epicenter depth, from 0 to 100 km with respect to solar cycles 20 to 23. This is important to investigate which epicenter depth of earthquake corresponds better with solar activity. We separate earthquakes into shallow and deep ones, with epicenter depth above and below 40 km, respectively. Figure 7 shows the superposition of yearly number of shallow earthquake and sunspot number (SSN) during solar cycles 20 to 23. In general, we can see the number of earthquakes keeps increasing and reaches the maximum number during the descending phase of solar cycle 23. More interestingly, one can see clearly the numbers of earthquakes are higher during lower sunspot number especially during minimum phases of solar cycles 21 to 23. We also examine the number of earthquakes at deeper depth, from 40 to 100 km as shown in Figure 8. The number of earthquakes steadily stays at average 1000 events before suddenly increased during descending phase of solar cycle 23. From both Figure 7 and 8, we can see that the solar activity phases are corresponding better to earthquake with shallow (< 40 km) epicenter depth.

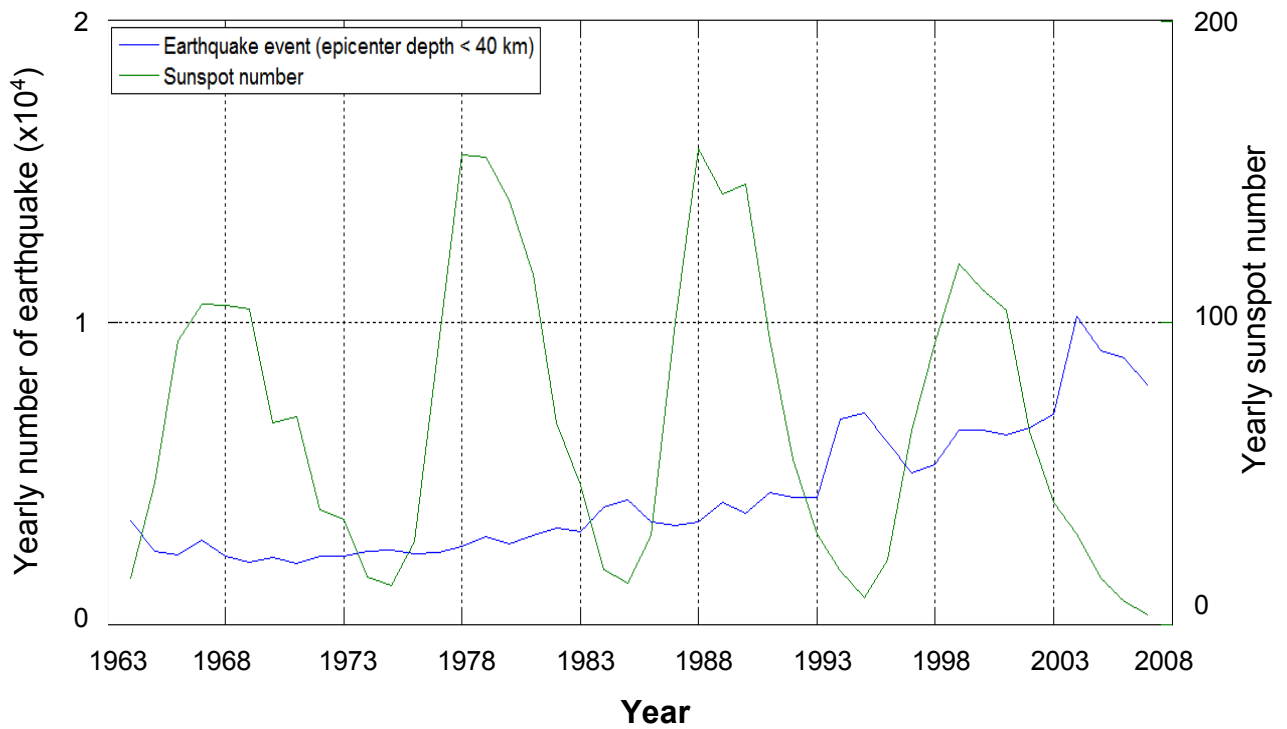


Figure 7: Superposition of yearly number of earthquake at epicenter depth < 40 km with sunspot number during solar cycle 20 to 23

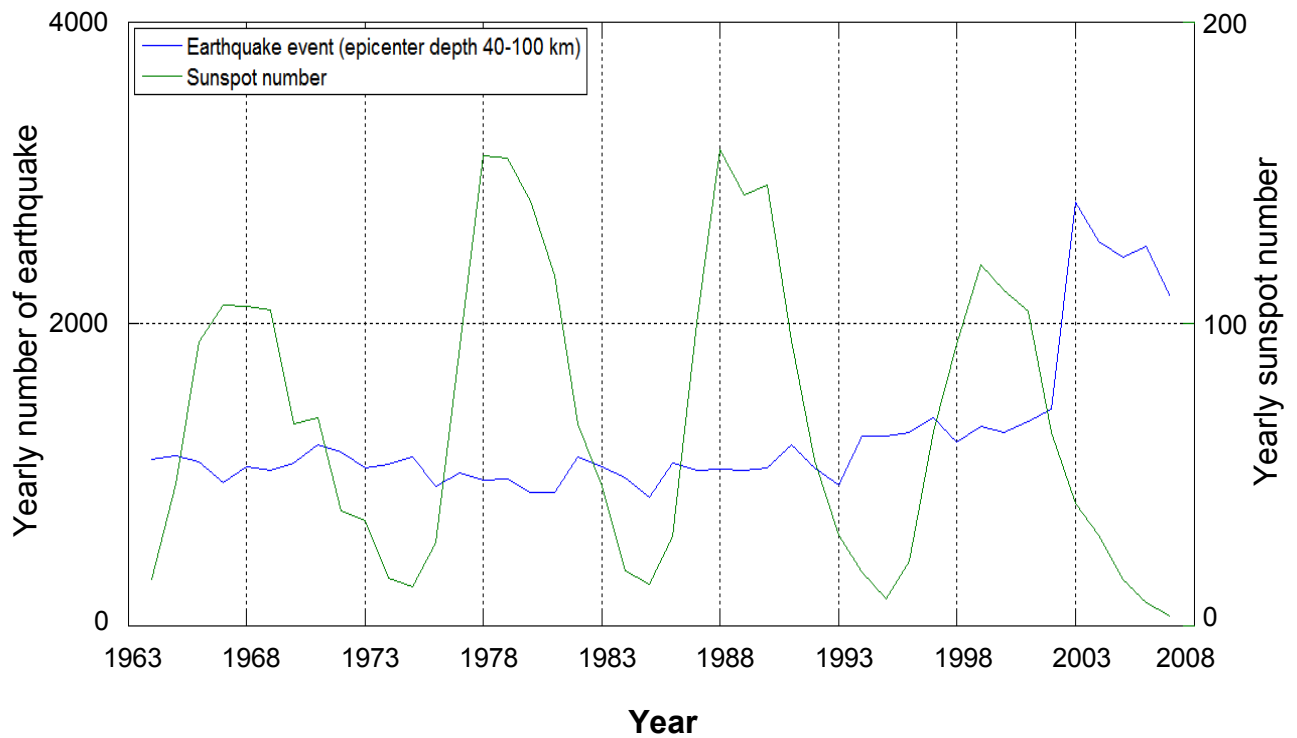


Figure 8: Superposition of yearly number of earthquake at epicenter depth 40-100 km with sunspot number during solar cycle 20 to 23

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 9 for the case of shallow (< 40 km) earthquakes and Figure 10 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 9, we can see that the largest number of shallow earthquakes is observed at the lowest level of sunspot number below 20 with $\sim 56,000$ 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 also can 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 the number of shallow earthquake.

Overall, more earthquakes seem to occur at lower range of sunspot number. 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 earthquake at epicenter depth between 5-25 km occurred more frequently after the high power electromagnetic pulses injected into the earth crust. This shows the possibility of shallow earthquakes to be triggered by external sources. However, more investigations on extraterrestrial and terrestrial factors are needed to confirm this expectation.

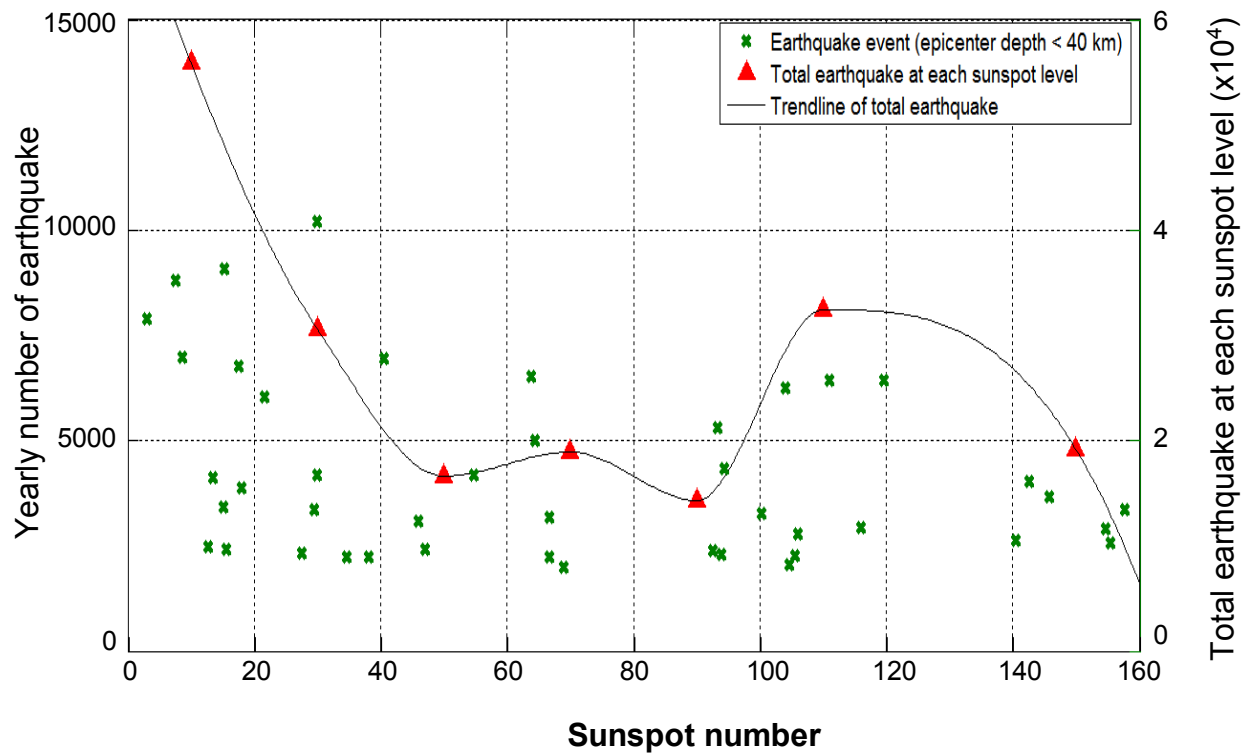


Figure 9: Variation of yearly shallow earthquake event with respect to sunspot number

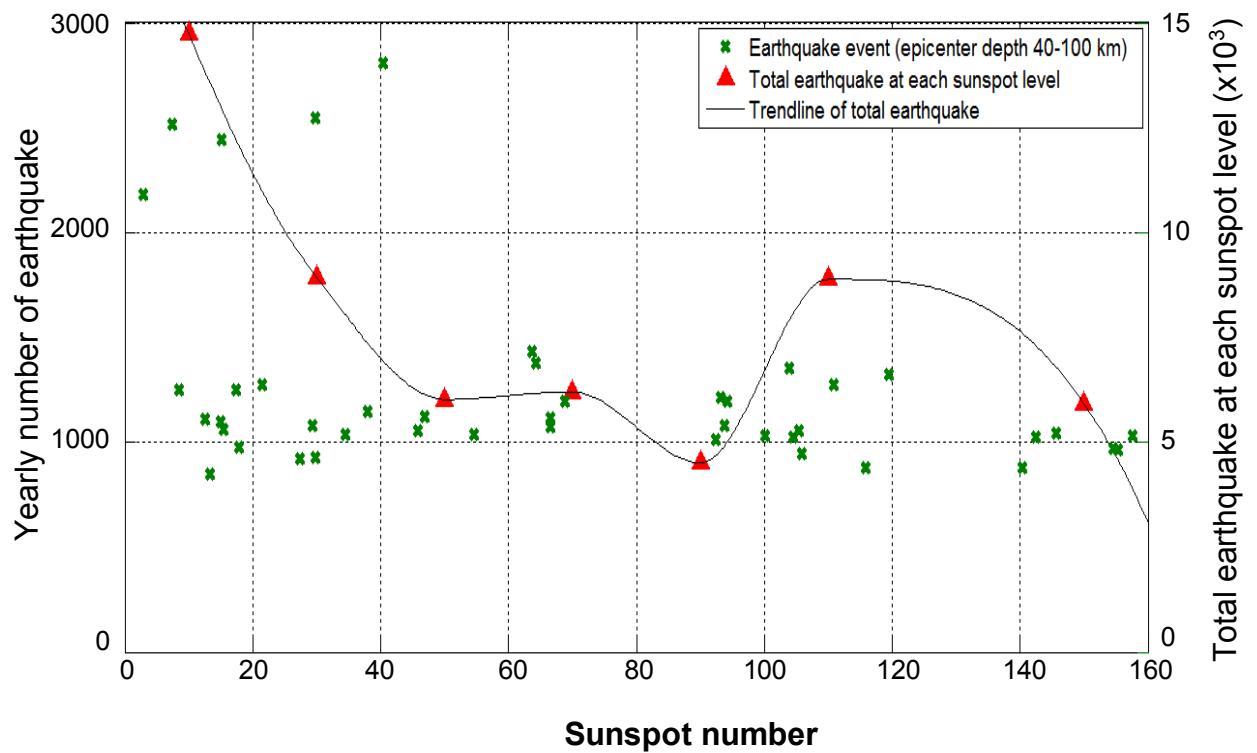


Figure 10: Variation of yearly deep earthquake event with respect to sunspot number

3.3 Variation of Global Earthquake Energy with Solar Cycles

The main purpose of the analysis is to analyze the total energy of earthquake instead of the total number of earthquake. A large number of small earthquakes could have the same amount of energy released from small number of big earthquakes.

Figure 11 shows the superposition of yearly sunspot numbers during solar cycle 20 to 23, from year 1963 to 2009 (green lines) with the energy released in earthquakes (red lines). This earthquake energy was calculated from earthquake with magnitude 4.0 to 9.9, with epicenter depth less than 100 km. The limit of epicenter depth is a consideration of possible external influenced on shallow and moderate earthquake events. It clearly shows that during descending and minimum phase of solar cycle 21 to 23, the amount of energy released from earthquake is greater than during other phases of solar cycle.

This pattern was confirmed by the graph shown in Figure 12. As we can see, the percentage of energy released from all earthquakes with magnitude 4.0 to 9.9 shows higher during descending and minimum phases of solar cycles 21 to 23. The percentage of earthquake energy during descending and minimum with ascending and maximum phases of solar cycle 20 was 49% and 51% respectively; only 2% differences. However, the percentage of energy released during descending and minimum phases of solar cycles 21 and 22 have increased to 58%, 16% higher than the energy released during ascending and maximum phases of solar cycles 21 and 22. This difference rapidly increased during solar cycle 23, where the descending and minimum phase contributes 78% compared to other phase of solar cycle. The big difference in energy released from earthquake was contributed mainly from the increase of big earthquakes during descending and minimum phase of solar cycle 23.

We investigate further the global earthquake released energy during solar cycle 20 to 23 at different epicenter depth for shallow (epicenter depth < 40 km) and deep earthquakes (epicenter depth 40-100 km) as shown in Figure 13 and 14 respectively. The earthquake energy from shallow epicenter depth shows higher tendency to release more during descending period of solar cycles as can be seen in Figure 13. However, for deeper depth earthquakes, as in Figure 14, it is hardly to see any significant variation of earthquake energy with solar cycles. These trends suggest that the shallow depth earthquake has a better possibility to relate with solar activity as compared to deep one.

The tendency of earthquake released energy to be higher during the declining phase of solar cycle has also been demonstrated by Odintsov et al., [2006]. They have analyzed the variations in the energy of earthquake events from year 1900 to 2000 by averaging all the earthquake magnitudes greater than 5 Richter scale. For our analysis, we have re-examined the results by extending the analysis to the most recent solar cycles. In addition, we also notice a long-term increasing trend of earthquake released energy with the recent 4 solar cycles.

Overall, we can see that the higher magnitude of earthquakes play significant roles in the earthquake released energy as compared to the occurrence number of earthquakes. This is due to the energy of earthquake is an exponential function of the magnitude. For example, for every 1 magnitude increase of earthquake, the energy will be increased by 32 times.

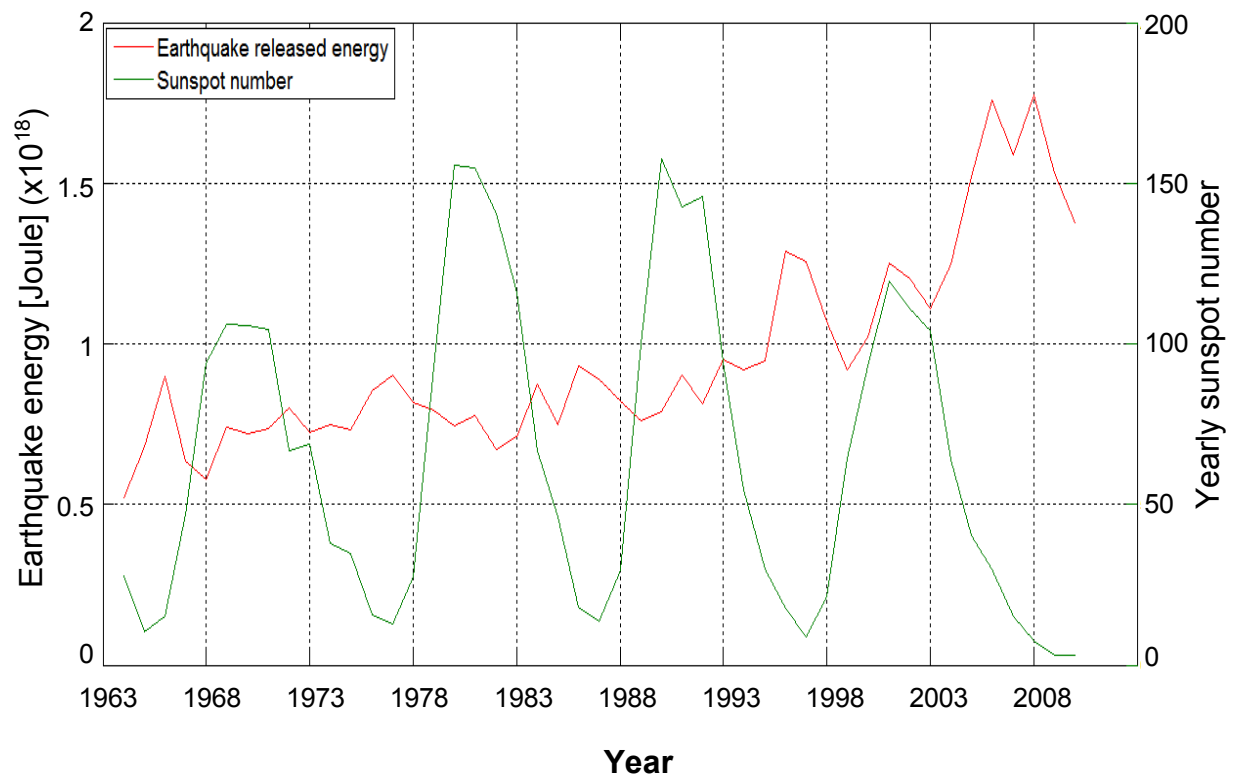


Figure 11: Superposition of yearly earthquake energy with respect to sunspot number

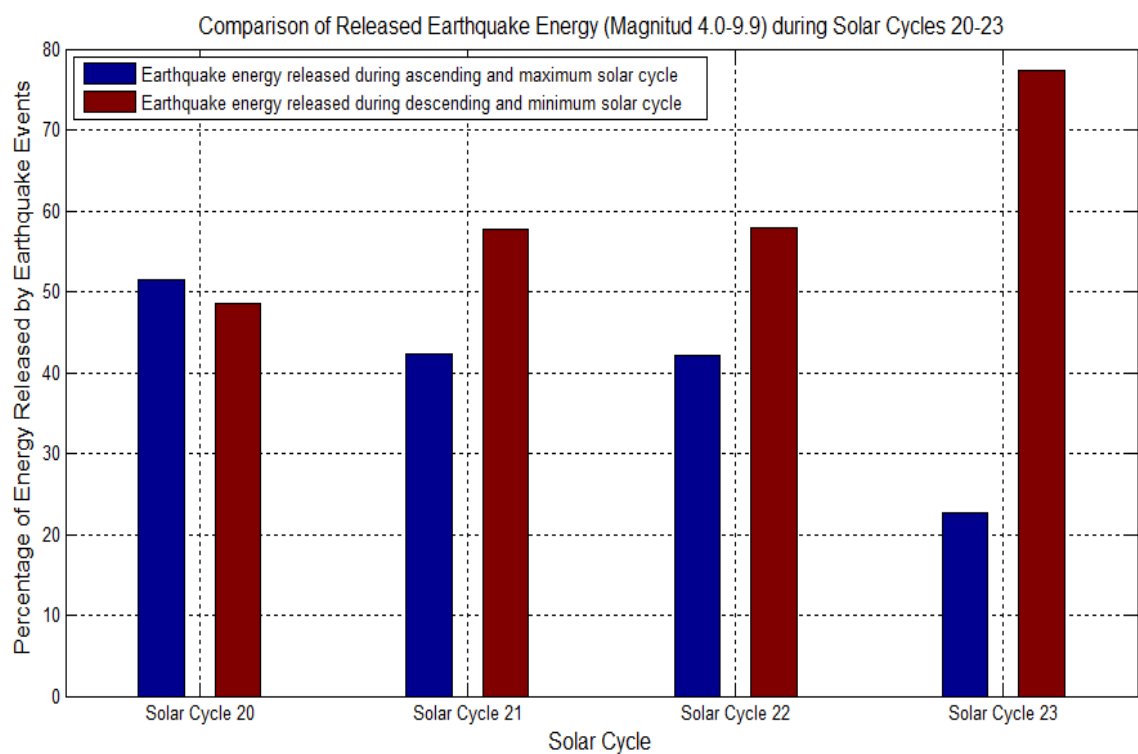


Figure 12: Earthquake Released Energy during Solar Cycle 20 to 23

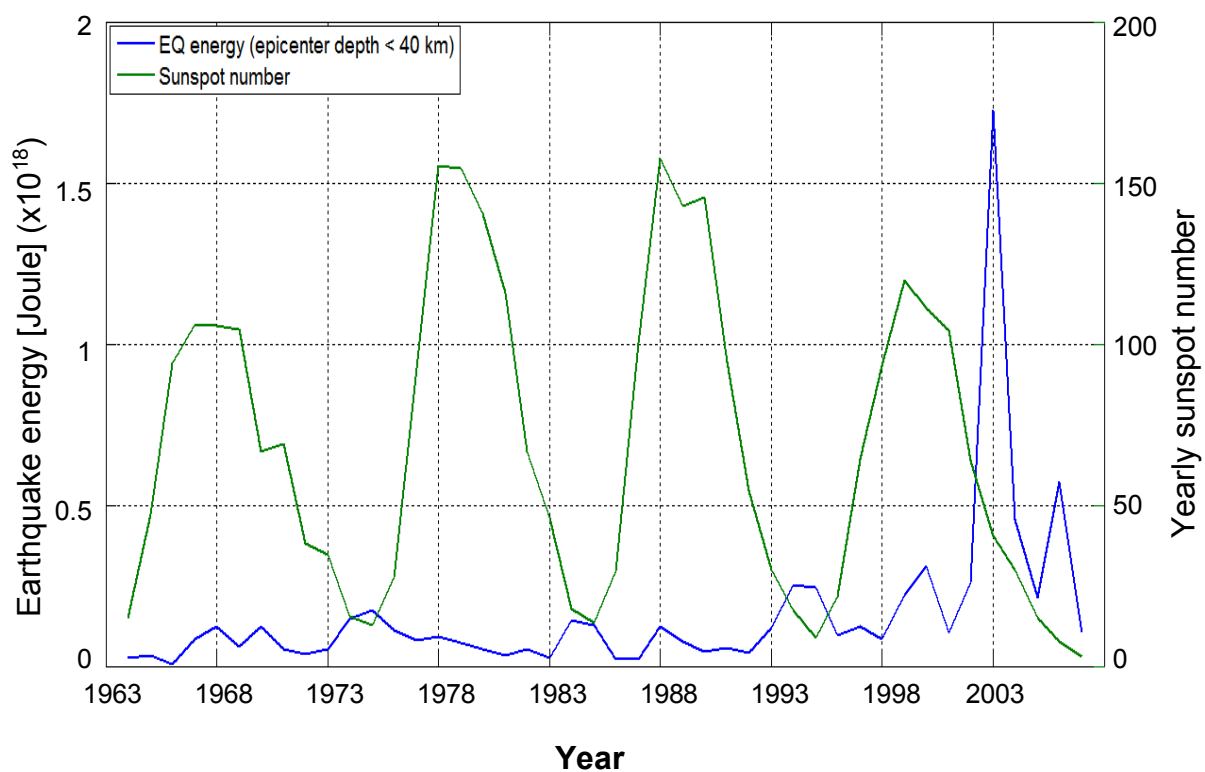


Figure 13: Superposition of yearly shallow earthquake energy (epicenter depth < 40 km) and sunspot number

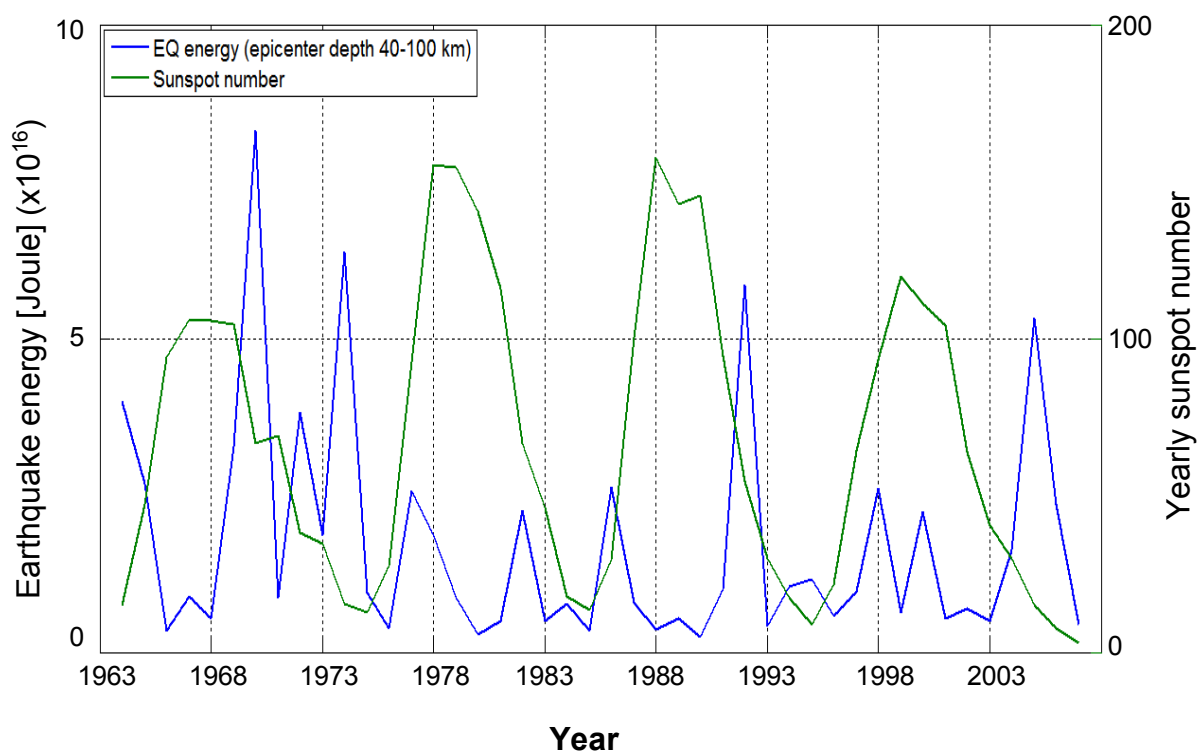


Figure 14: Superposition of yearly shallow earthquake energy (epicenter depth 40-100 km) and sunspot number

3.4 Distribution of regional earthquake energy

To examine the possible relationship between solar activity and local earthquake events, we have analyzed the occurrence of earthquake events at two most seismically active regions; Japan region and Sumatra (Indonesia) region during SC 20 to SC 23. The number of earthquake events for both regions has been categorized into two magnitude ranges; magnitude 4.0 – 5.9 and magnitude 6.0 – 9.0.

3.4.1 Japan region

Japan has had a long history of seismic activity. It is an area of high seismicity because it is located near major tectonic plate boundaries which are Asia plate, Philippine plate and Pacific plate.

To examine the tendency of earthquakes in Japan with solar activity, we have plotted the annual earthquake released energy during SC 20 to SC 23 for magnitude 4.0 to 5.9 and for magnitude 6.0 to 9.0 Richter scale as shown in Figure 15 and Figure 16, respectively. For both plots, X-axis shows the year of solar cycles while Y axis on the left scale shows the yearly earthquake energy in unit Joule represented by bars and Y-axis on the right scale shows the annual sunspot number represented by green line.

The results show that the earthquake released energy from both magnitude ranges tends to be higher during descending cycle of solar activity or sunspot number. For lower magnitude range of earthquake in Figure 15, we can see that the earthquake energy keeps increasing from the first year of solar cycle until the fifth year of solar cycle, during the maximum period of solar cycle. The energy decreased in the following year before increasing again and reaching the peak on the ninth year

(four years after sunspot maximum), during the descending period of solar cycle. However, the result from higher magnitude of earthquake in Figure 16 shows peak of the earthquake released energy observed on the third year after sunspot maximum. If we sum up the energy of earthquake from both magnitude ranges, it will give similar result with statistics demonstrated by Odintsov et al., [2007] where maximum amount of earthquake energy was observed during the third year after sunspot maximum.

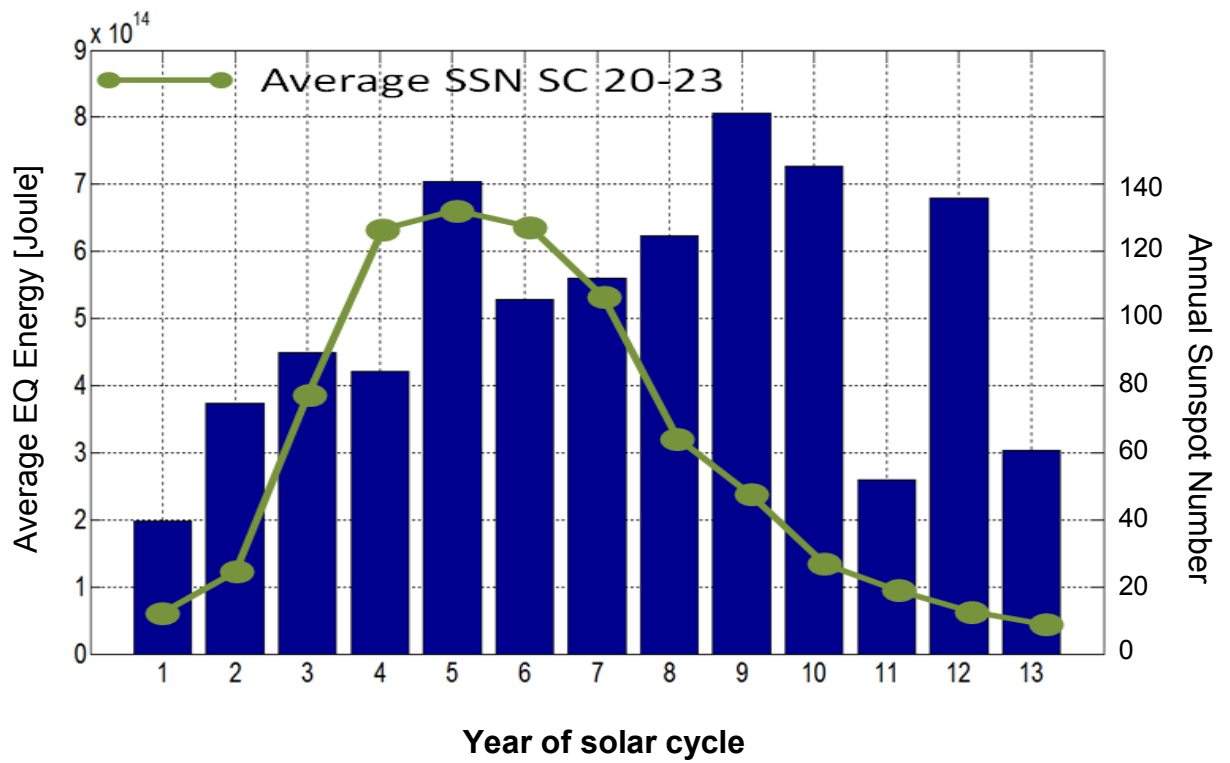


Figure 15: Yearly energy released by earthquakes of magnitude 4.0 – 5.9 during SC 20 – SC 23 for Japan region

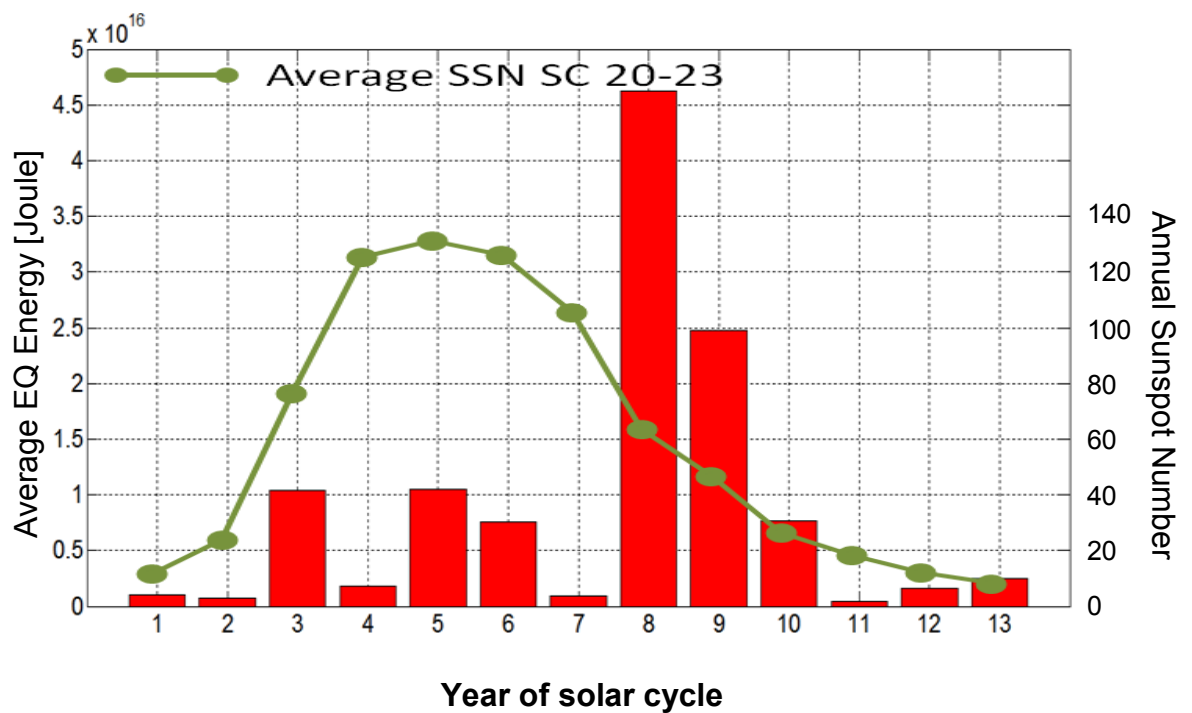


Figure 16: Yearly energy released by earthquakes of magnitude 6.0 – 9.0 during SC 20 – SC 23 for Japan region

3.4.2 Sumatra region

The Indonesian island of Sumatra is located in a highly seismic area of the world. In addition to the subduction zone and the associated Sunda Arc off the west coast of the island, Sumatra also has a large strike-slip fault, the so-called Great Sumatran Fault, running the entire length of the island. This fault zone accommodates most of the strike-slip motion associated with the oblique convergence between the Indo-Australian and Eurasian plates [Sieh and Natawidjaja, 2000].

To investigate the occurrence pattern of earthquakes at Sumatra region and relate them with solar activity, we have plotted the solar cycle distribution of the yearly earthquake released energy during solar cycle 20 to 23. The plots have been divided into 2 earthquake magnitude ranges; 4.0 to 5.9, in Figure 17 and 6.0 to 9.0 Richter scale in Figure 18. The labels of X and Y-axis in Figure 17 and Figure 18 are similar with the previous Figures 15 and 16. Both ranges of earthquake magnitudes from Sumatra region show less significance with maximum year of solar cycle. The maximum earthquake energy released occurs on the tenth and ninth year of solar cycles for lower magnitude range and higher magnitude range of earthquake, respectively. There is 1 year lag for both magnitude ranges as compared with the Japan region earthquake.

However, for both plots, we can see the same pattern where most of earthquake energy tends to be released during the descending phase of solar cycle. This trend is the same with that in Japan region and in global earthquake.

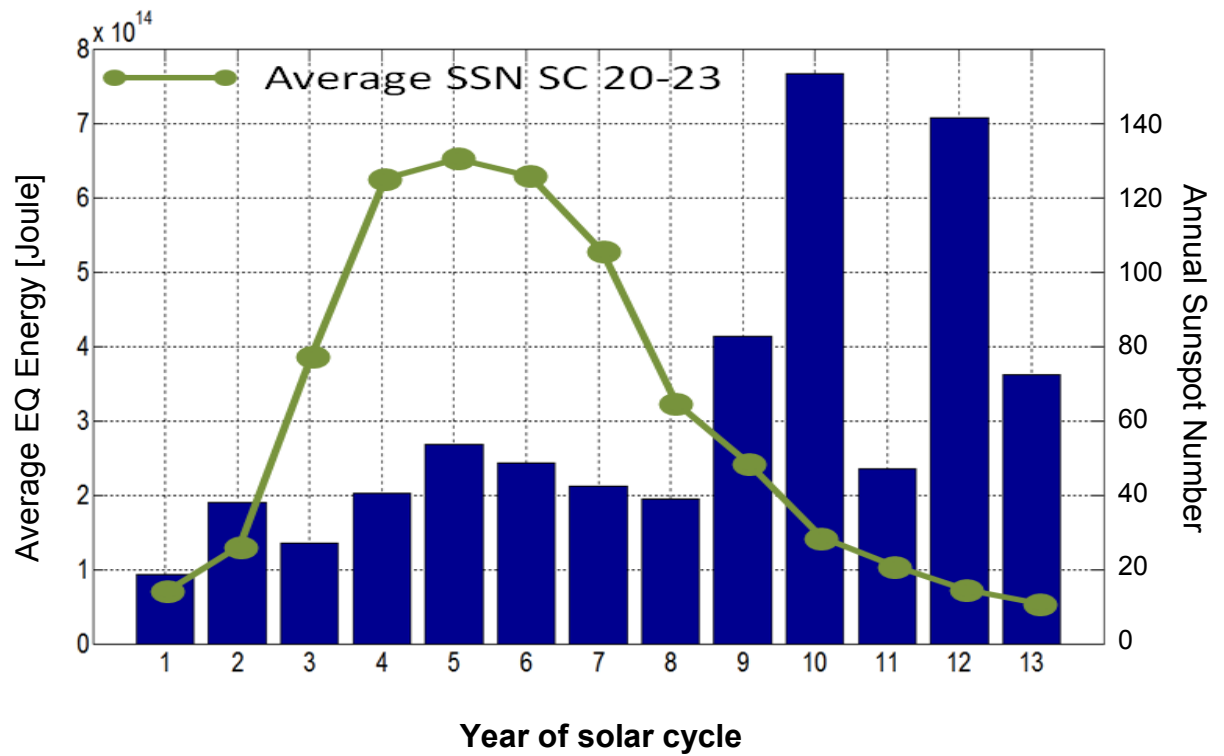


Figure 17: Yearly energy released by earthquakes of magnitude 4.0 – 5.9 during SC 20 – SC 23 for Sumatra region

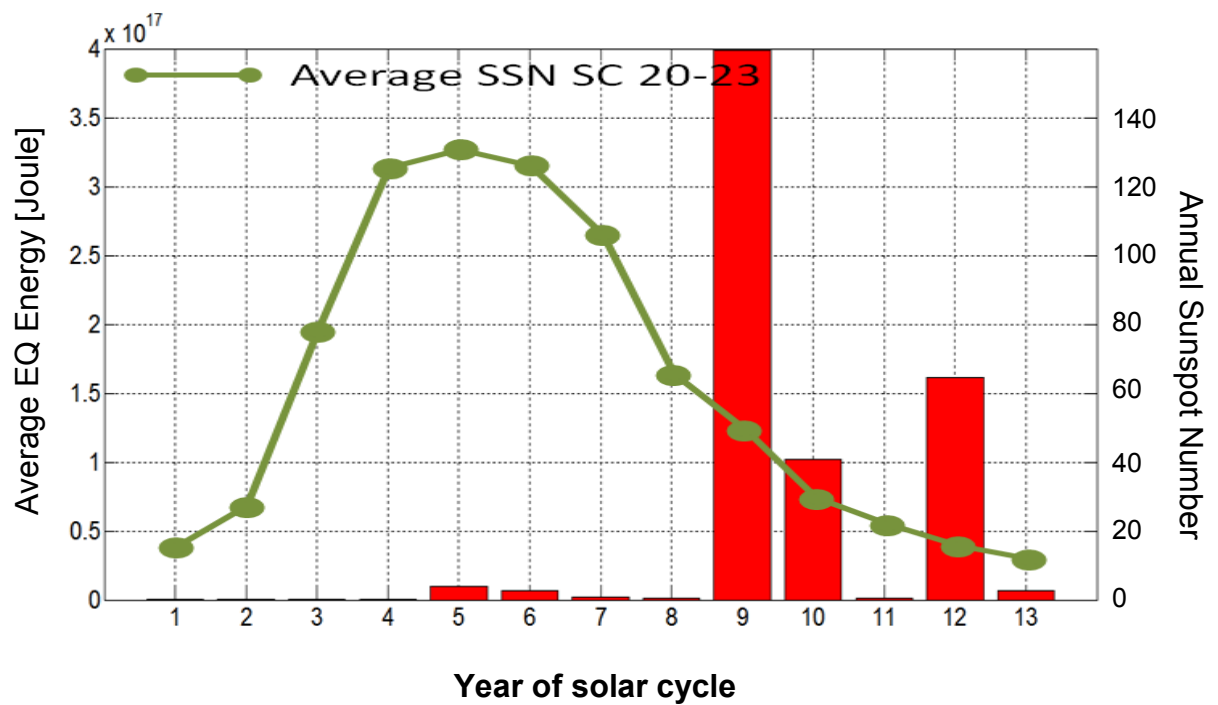


Figure 18: Yearly energy released by earthquakes of magnitude 6.0 – 9.0 during SC 20 – SC 23 for Sumatra region

3.5 Solar wind parameters associated with earthquakes

The correlation between solar wind and seismic activities has been demonstrated by a number of researchers [Sytinskii, 1997; Odintsov et al., 2006; Anagnostopoulos, 2012, to name a few], however, the possible physical mechanism that connecting solar wind and seismicity is not well established yet. Therefore, in order to examine the possible solar – seismicity coupling, in this study, we are investigating various possible aspects and parameters of solar wind e.g. high speed solar wind (HSSW), solar wind dynamic pressure (SW P_{dyn}) and solar wind input energy, epsilon (ϵ) with earthquake events at different magnitudes.

3.5.1 Relationship of earthquake with high speed solar wind (HSSW)

To examine the relationship between earthquake and HSSW [Lyatsky et al., 2007 and Gupta and Badruddin, 2010], we firstly monitor the yearly number of HSSW during solar cycle 23. The HSSW events shown in Figure 19 were selected based on the factors is mentioned earlier in Chapter 2. We can see that the number of HSSW event is higher during the descending phase as compared to ascending phase of solar cycle 23. The trend is similar to that of the amount of earthquake energy in Figure 20.

Figure 20 presents the solar cycle distribution of the average yearly energy released from global earthquake events at magnitude 4.0 to 9.9 Richter scale. Maximum energy is released during descending phase of solar cycle 23, coinciding with the number of HSSW detected in the previous figure. This similarity shows a possible relation between them. Therefore, further analysis is needed to examine their relationship.

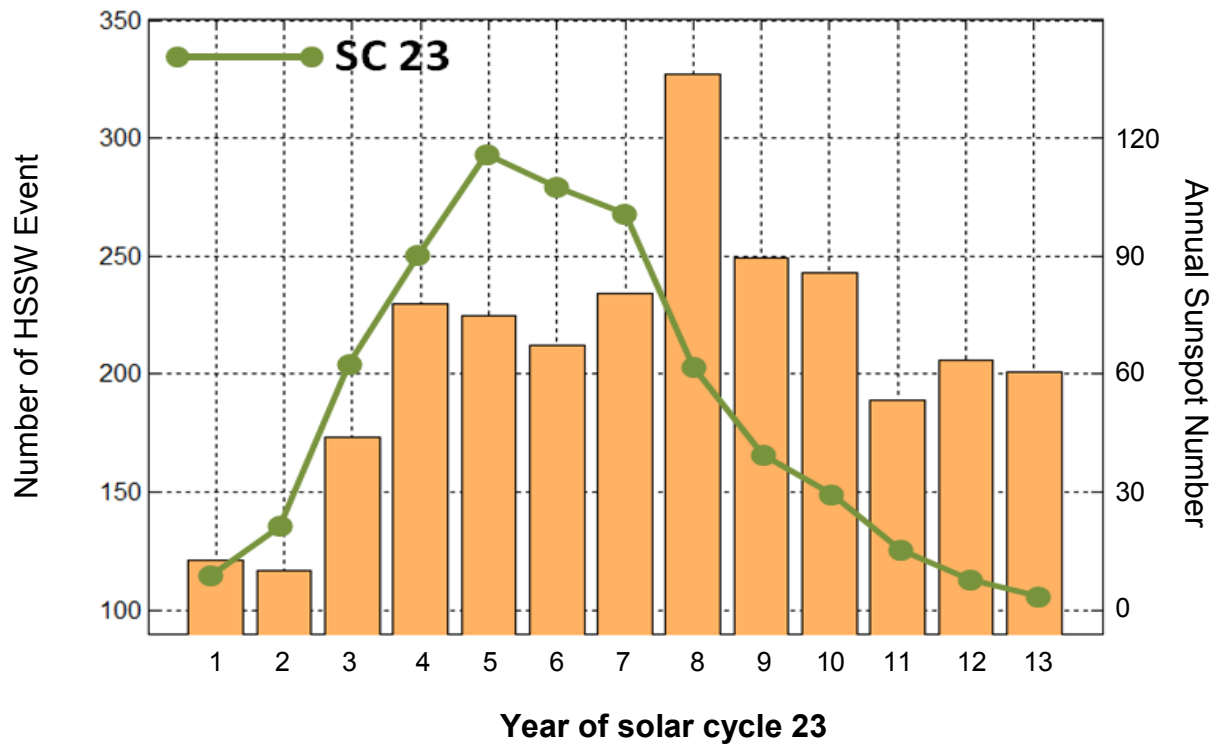


Figure 19: Yearly number of high speed solar wind event during solar cycle 23

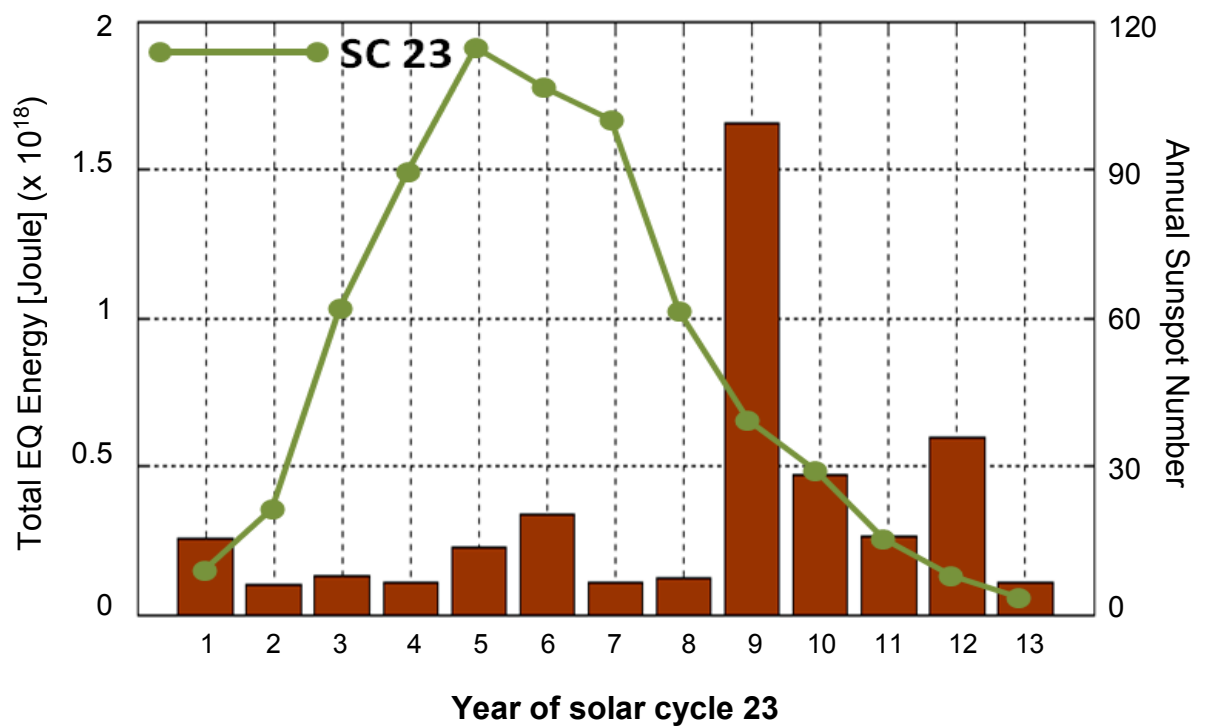


Figure 20: Yearly earthquake energy released during solar cycle 23

The plot for day-to-day variation of big earthquake events (magnitude 6.0 or greater) with respect to HSSW is shown in Figure 21. It is a correlation analysis of earthquake with respect to the days of arrival of HSSW. X axis represents the day of arrival of HSSW (0), one day before and one day after the arrival of the HSSW (-1 and +1, respectively), etc. Y axis represents the correlation coefficient between earthquake event and HSSW. The analysis was done for the period of 4 days before and 4 days after the arrival of HSSW event from year 1964 to 2008, covering 4 solar cycles 20 to 23. For this analysis, we have calculated the correlation coefficient between earthquake and HSSW events for each day of arrival of HSSW by shifting the earthquake events from 4 days before to 4 days after the arrival of HSSW.

The result shows correlation coefficients keep increasing from 4 days before the arrival of HSSW event and reached maximum one day after the arrival of HSSW. The value of correlation coefficients decreased on the following days. From 1603 cases of HSSW within this period, 997 events or 62% were recorded on the day or within 4 days before the big earthquake events. Even though the values of correlation coefficients are low, the observation within this range suggests that, the period of 1 day after the arrival of HSSW corresponds well with the seismic events. Gousheva et al., [2003] has compared the occurrence of global earthquake at magnitude 5.5 and greater with the HSSW during year 1973 to 2000 and obtained similar result.

The percentage of big earthquake events with respect to HSSW can be referred in Figure 22. The pie chart shows that the percentage of earthquake occurred 4 days before HSSW, on the day of HSSW and 4 days after HSSW are 26%, 9% and 35% respectively. Only 30% out of 4108 big earthquake events not relate to the arrival of HSSW. To relate with HSSW, only 46% of earthquake events occurred on the day of

the arrival of HSSW (10%) and within 4 days after HSSW (36%). Another 54% of earthquakes occurred before the arrival of HSSW (25%) and beyond the observation time (29%). We assume that, these 54% of earthquakes have no relationship with HSSW. This shows that HSSW could trigger more earthquakes but the HSSW event is not the only factor triggering the earthquake events. Earthquake events could be triggered or caused by other geophysical factors such as the movement of tectonic plates, accumulation of underground static dynamic stress [Kilb et al., 2000], crustal faulting [Boatwright, 1997] and many more.

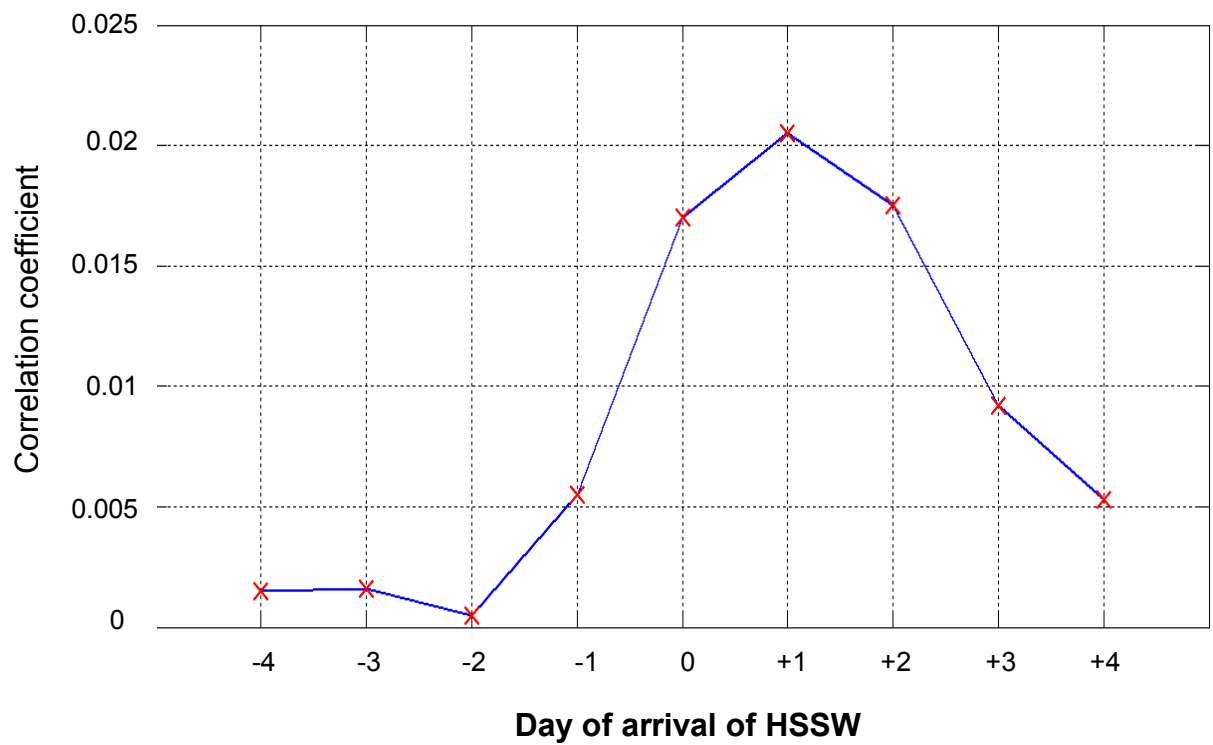


Figure 21: Correlation coefficient between earthquake and high speed solar wind

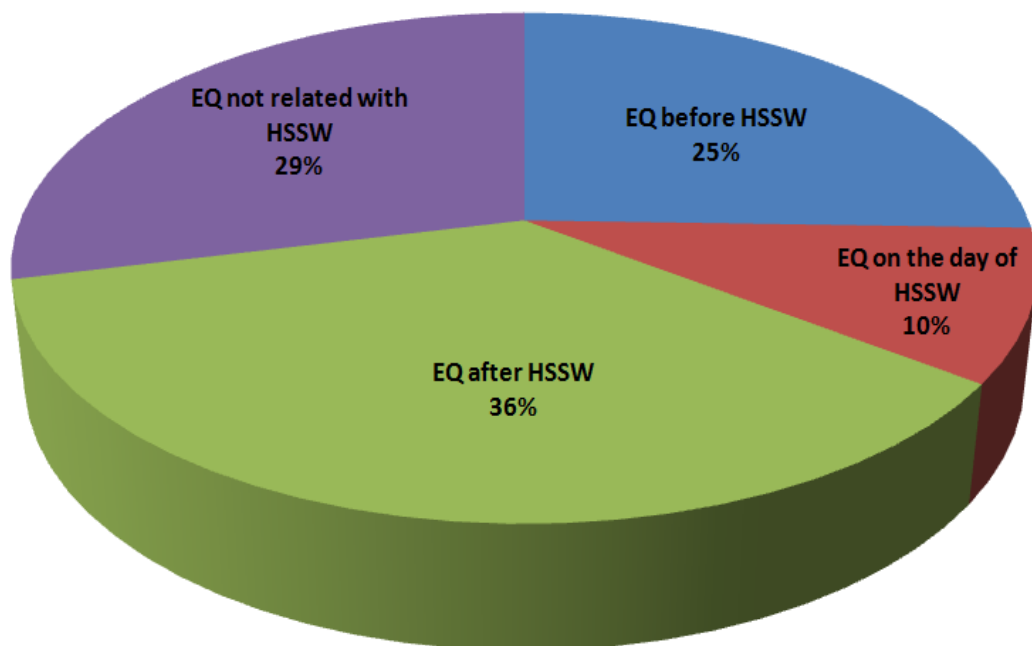


Figure 22: Percentage of Earthquake Events with respect to HSSW

We further analyze the periodicity of solar wind speed based on the power spectrum analysis as shown in Figure 23. According to the figure, solar wind speed shows a prominent peak at around 9 days period during year 2005. To examine whether global earthquake events have the same periodicity, we compared the power spectrum of shallow earthquake events at epicenter depth < 40 km and deep earthquake events at epicenter depth 40-100 km as shown in Figure 24 and 25 respectively. The plots show no significant peak around 9 days. This suggests that, there is no one to one correspondence between solar wind speed and global earthquake activity.

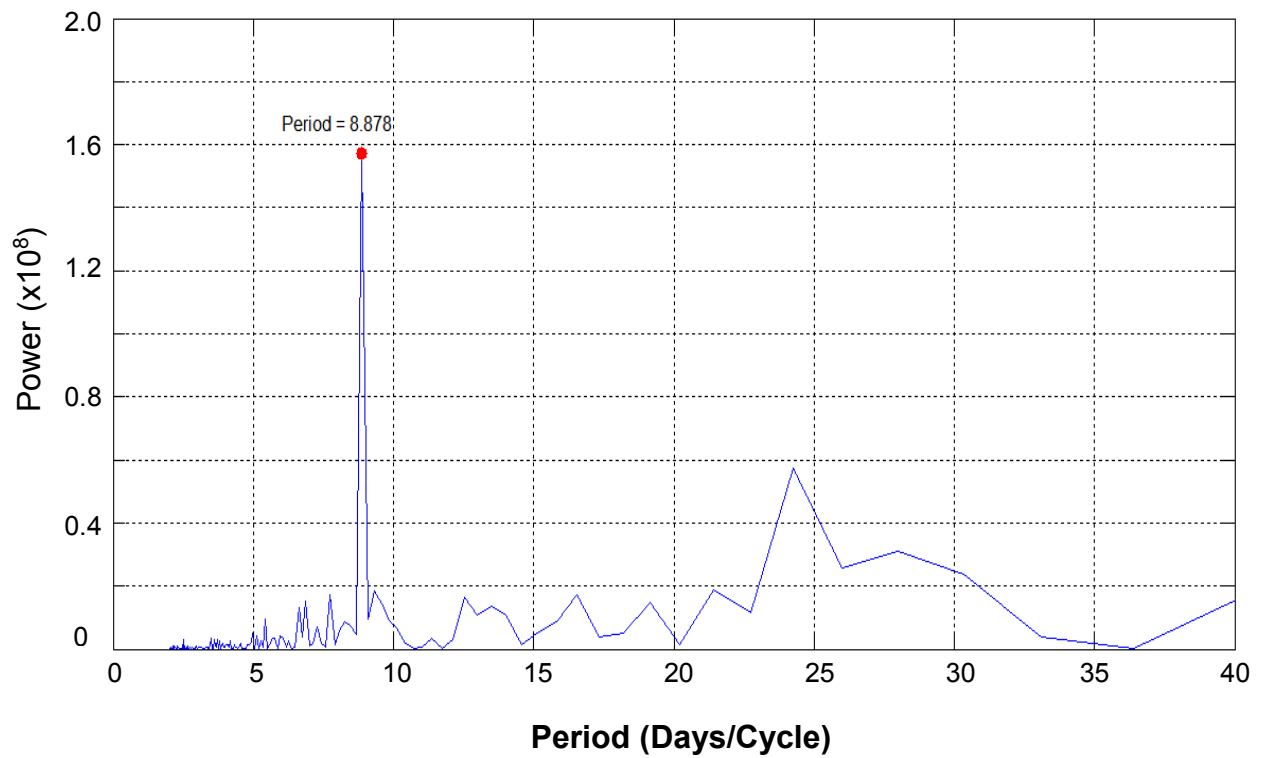


Figure 23: Power spectrum analysis for solar wind speed during year 2005

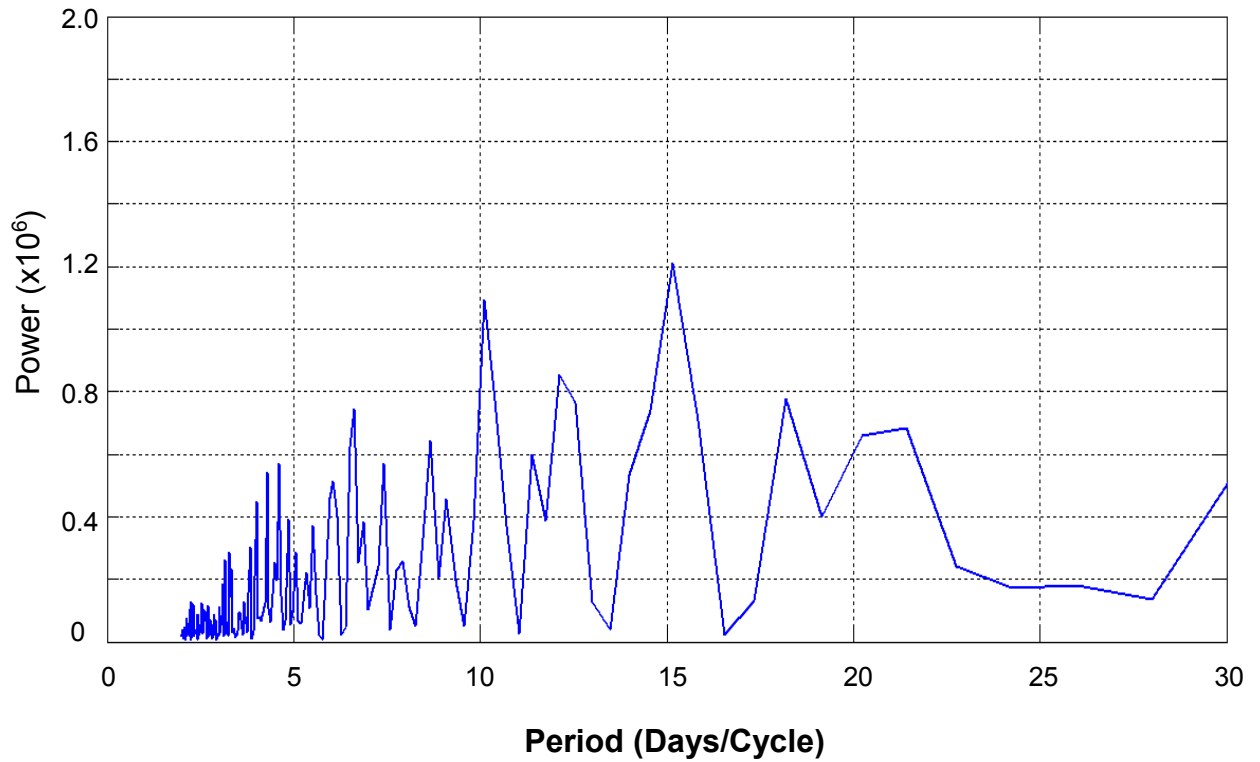


Figure 24: Power spectrum analysis for global earthquake at epicenter depth < 40 km during year 2005

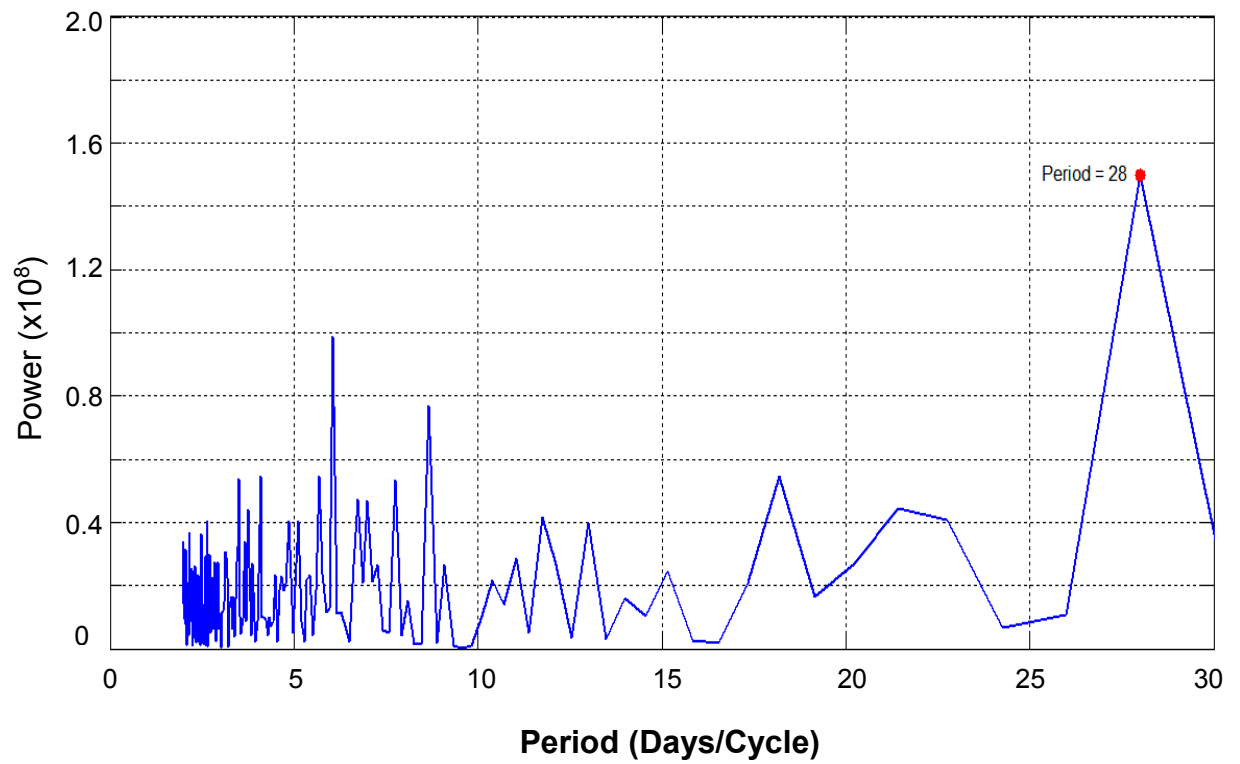


Figure 25: Power spectrum analysis for global earthquake at epicenter depth 40-100 km during year 2005

3.5.2 Relationship of EQs with High Solar Wind Dynamic Pressure

In space weather study, the effects of solar wind to the earth system are very significant. Solar wind dynamic pressure enhancements are known to cause various types of disturbances to the magnetosphere. Solar wind dynamic pressure sometimes increases abruptly. The effect of such an abrupt increase on various types of magnetospheric phenomena has long been a subject of active research. The types of effects include ground magnetic disturbances [Russell et al., 1994], geosynchronous magnetic field response [Lee et al., 2004], geosynchronous energetic particle disturbance [Lee et al., 2005], auroral disturbance [Lyons et al., 2000; Zesta et al., 2000; Boudouridis et al., 2003], and energetic neutral atom response [Lee et al., 2007].

Since solar wind dynamic pressure is a function of solar wind speed, and is able to affect the magnetospheric and ionosphere, it is worthwhile to evaluate the statistical significance of dynamic pressure with the occurrences of earthquake events. To our knowledge, there is no reported work on this topic so far.

To examine the possible relationship of dynamic pressure with the earthquake event, we have statistically compared the yearly SW P_{dyn} and the energy released from earthquakes during solar cycle 22 as shown in Figure 26 and Figure 27, respectively. The annual SW P_{dyn} in unit nano Pascal (nPa) was plotted during the 11-year period of solar cycle 22. We can see the SW p_{dyn} is higher on the sixth year of solar cycle 22 before decreasing in the following years. On the tenth and eleventh year, the SW P_{dyn} increased abruptly. The annually averaged energy from earthquake shows the similar pattern (Figure 27). Annually averaged earthquake energy increased tremendously during the last two years of solar cycle 22 to more than 2.5×10^{17} Joule, nearly double of that in previous years of solar cycle 22 with

average energy only around 1.3×10^{17} Joule. The similarity between the annually averaged of SW Pdyn and earthquake energy during 11-year period of solar cycle 23 shows the possible interconnection between them. Therefore, it is necessary to further analyze both parameters to establish a better explanation for the possible influence of SW Pdyn to the earthquake events.

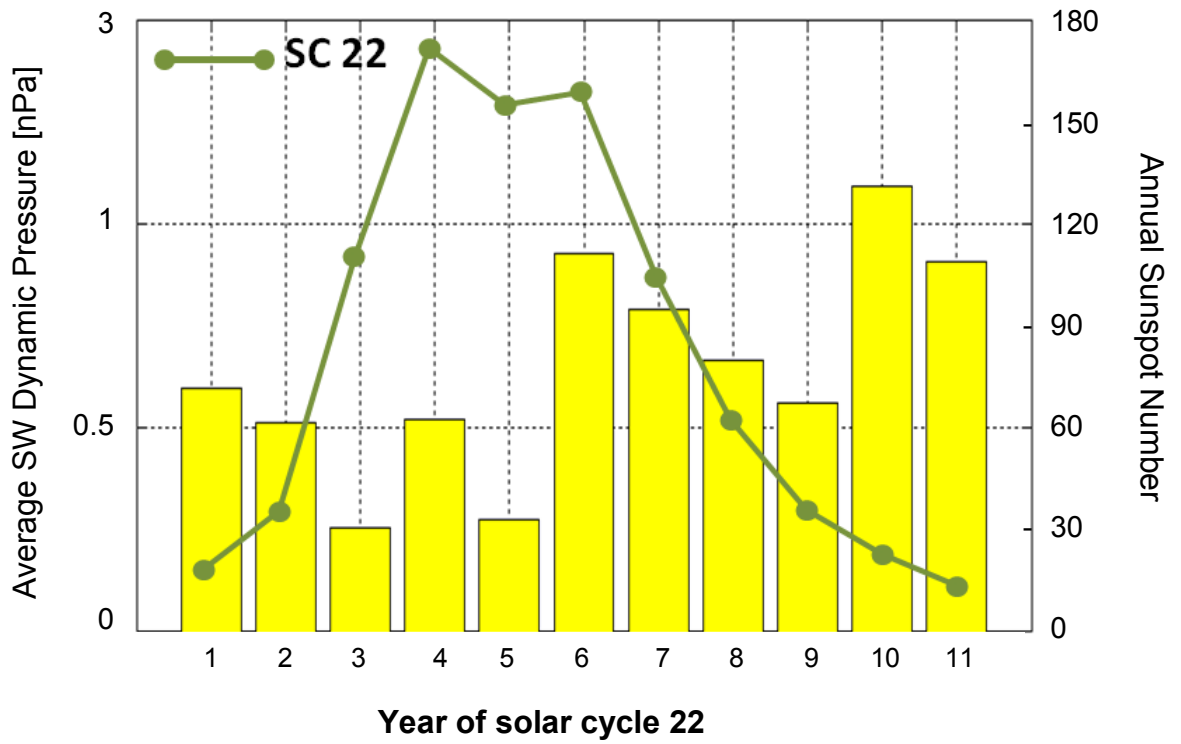


Figure 26: Yearly solar wind dynamic pressure during solar cycle 22

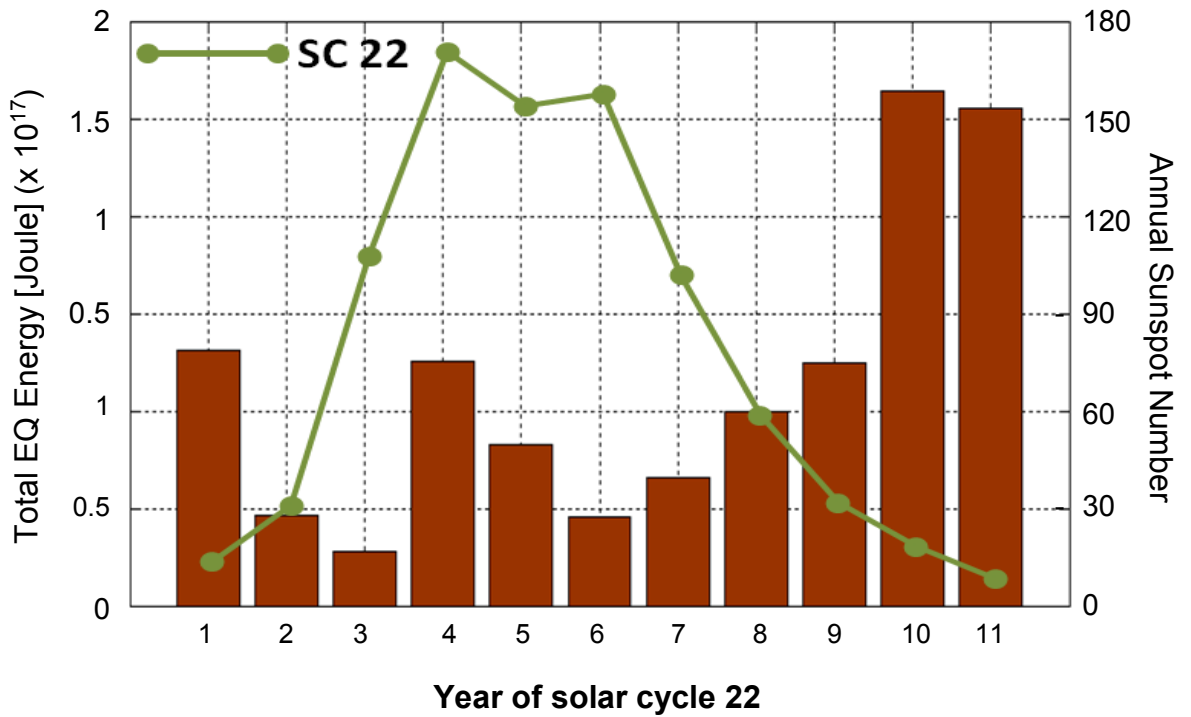


Figure 27: Yearly total earthquake energy during solar cycle 22

According to our preliminary analysis, the average daily value of SW Pdyn is 2.12 nPa. Based on this result, the value of 3 nPa has been chosen as upper threshold value to compare the day to day variation of high SW Pdyn with the occurrences of EQ events.

In Figure 28, we have compared the day-to-day variation of correlation coefficient for global earthquake events at magnitude 5.0 to 9.9 Richter scale with respect to the day of observed high SW Pdyn during solar cycle 23. In the graph, X-axis represents the day of observed high SW Pdyn (0 day), 1 day before and after the detected high SW Pdyn (- 1 day and + 1 day respectively), etc. Y-axis represents the correlation coefficient between earthquake event and high SW Pdyn. The correlation coefficients are calculated by varying the onset time of earthquake event from 4 days before until 4 days after of high SW Pdyn. In the graph, we can see the value of correlation coefficients keeps increasing from 4 days before the high SW Pdyn and reached maximum 1 day after (+1) the high SW Pdyn. Even the values of cross correlations are low for this analysis, one can assume that if there is possible connection between solar wind dynamic pressure and seismic activity, the period of 1 day after high solar wind dynamic pressure detected is corresponding with the seismic activity. This correlation is similar with the trend between earthquake events and HSSW. The similarity of both parameters (HSSW and SW Pdyn) with earthquake events suggests a mutual mechanism connecting solar activity and seismicity.

The pie chart in Figure 29 shows the average fraction of earthquake events with respect to different time lag of high SW Pdyn onset day. Referring to the chart, 54% of earthquakes occurred on the day or 4 days after the observed high SW Pdyn events. Another 46% of earthquakes occurred within 4 days before the observed of

high SW Pdyn and beyond the observation time with percentage 21% and 25% respectively.

Based on this analysis, statistically the SW Pdyn shows a good correspondence with earthquake events where the higher amplitude of SW Pdyn tends to trigger more earthquakes. However, further analysis is necessary to concretely establish the relationship between SW Pdyn and seismic activities since we are not sure what is (or are) the direct connecting parameters connecting them.

To date, several researchers have done different part of study which could be possibly considered as connecting events/parameters. Choi et al., [2008] statistically investigated the effect of SW Pdyn enhancements during geomagnetic storms. They reported that enhancement of SW Pdyn can be a substorm trigger under a prolonged southward of interplanetary magnetic field (IMF) condition. Other studies by Zhou & Tsurutani, [2001] and Shi et al., [2006] also show promising results connecting SW Pdyn with geomagnetic storm.

In another aspect of study, Mukherjee, [2002] monitored the planetary index, Kp and Coronal mass ejection (CME) events and gives a hypothesis that the explosive events on the sun will transfer the energy into magnetosphere and generating geomagnetic storms which occasionally may affect the active faults to trigger shallow depth of earthquake. Han et al., [2004] reported that the occurrence of many geomagnetic storms will produce stronger eddy current in the lithosphere, then generates more heat and triggers more earthquakes events in China and western Mongolia.

By referring to both aspects of studies, it could be possible to consider geomagnetic storm as one of the connecting parameters between the high SW Pdyn and seismic activities. However, the investigation on the influence of geomagnetic

storms at various geographical regions could give different relationship due to the latitudinal dependence on storm activities. These possibilities warrant further studies.

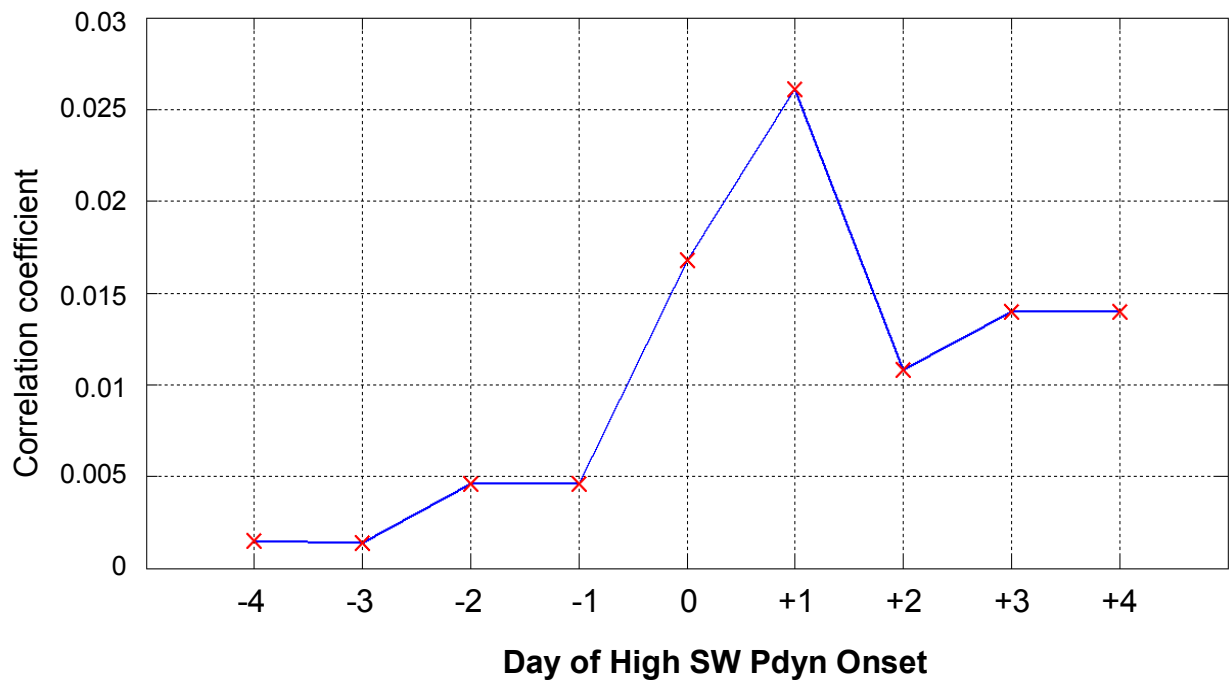


Figure 28: Correlation coefficient between high solar wind dynamic pressure and earthquake (magnitude 5.0-9.9) during SC 23.

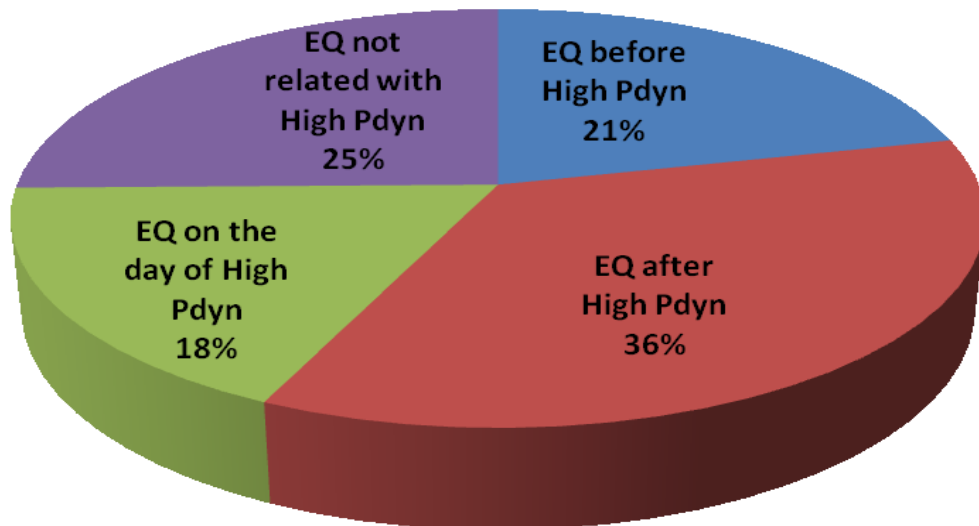


Figure 29: Percentage of earthquake with respect to day of high solar wind dynamic pressure

3.5.3: Relationship of Earthquakes with Solar Wind Input Energy

Solar wind is the source of energy for magnetospheric processes. Understanding how the solar wind energy source couples to the magnetosphere is a main task in magnetospheric physics, and it is essential to space weather study. The transfer of solar wind energy to the magnetospheric system is primarily controlled by the orientation of the interplanetary magnetic field (IMF). One of the earliest and most widely used coupling functions is Akasofu's epsilon parameter [Perreault and Akasofu, 1978; Akasofu, 1981]. The relationship was quantified empirically which essentially represents a rectified Poynting flux from the solar wind. As mentioned earlier in Chapter 2 (section 2.1.3), the function of $F(\theta)$ in the formula (3) is the key point which controls the penetration of solar wind input energy to the earth's magnetosphere.

Zhang, [1998] reported the correlation analysis between earthquake events ($M \geq 6$) and sunspot numbers, solar 10.7 cm radio flux and solar proton events. It was found that when the maximum annual means of sunspot number is large, the earthquake frequency in the next minimum period of sunspot number (in three years around the minimum year) is also large. The author suggests that the lag correlation of these phenomena is due to the fact that effects of solar energy to the earth surface and its inner core may need some time to accumulate before exceeding the earth elastic limits to trigger the earthquake events. However, no statistical evidence has been made to establish this idea.

To further confirm this idea, we have made estimation of the average amount of solar wind input energy and the average energy released from earthquake. According to the calculation of earthquake energy by Kanamori, [1983] as in formula (1), the estimation of average energy from earthquake is 1×10^7 Joule (earthquake

magnitude ~ 2) while Akasofu, 1981 estimates the average SW input energy is 4.3×10^{15} Joule.

The amount of SW input energy penetrates into the earth's magnetosphere is relatively big as compared with the average energy released from earthquake event. Even though not all (100%) of the SW input energy will penetrate into the lithosphere (due to dissipation process) it is possible to consider this energy as one of the energy source for earthquake.

Before we analyze further the possible relationship of SW input energy and earthquakes, we firstly examine the variation of the total annual SW input energy with solar cycle 23 as plotted in Figure 30. X-axis represent the year of solar cycle 23 while the Y-axis represents the total annual SW input energy in unit of Joule. From the figure, higher SW input energy occurred during the descending phase of solar cycle 23, with maximum value on the ninth year of solar cycle 23. If we compare this trend with the annual average variation of earthquake energy during the same period of solar cycle 23 as shown earlier in Figure 20, we can see the similar trend exists in earthquake released energy but with 1 year delay. This delay could be possibly explained by process of accumulation of energy in the lithosphere before it discharges by triggering earthquakes as suggested earlier by Zhang, [1998].

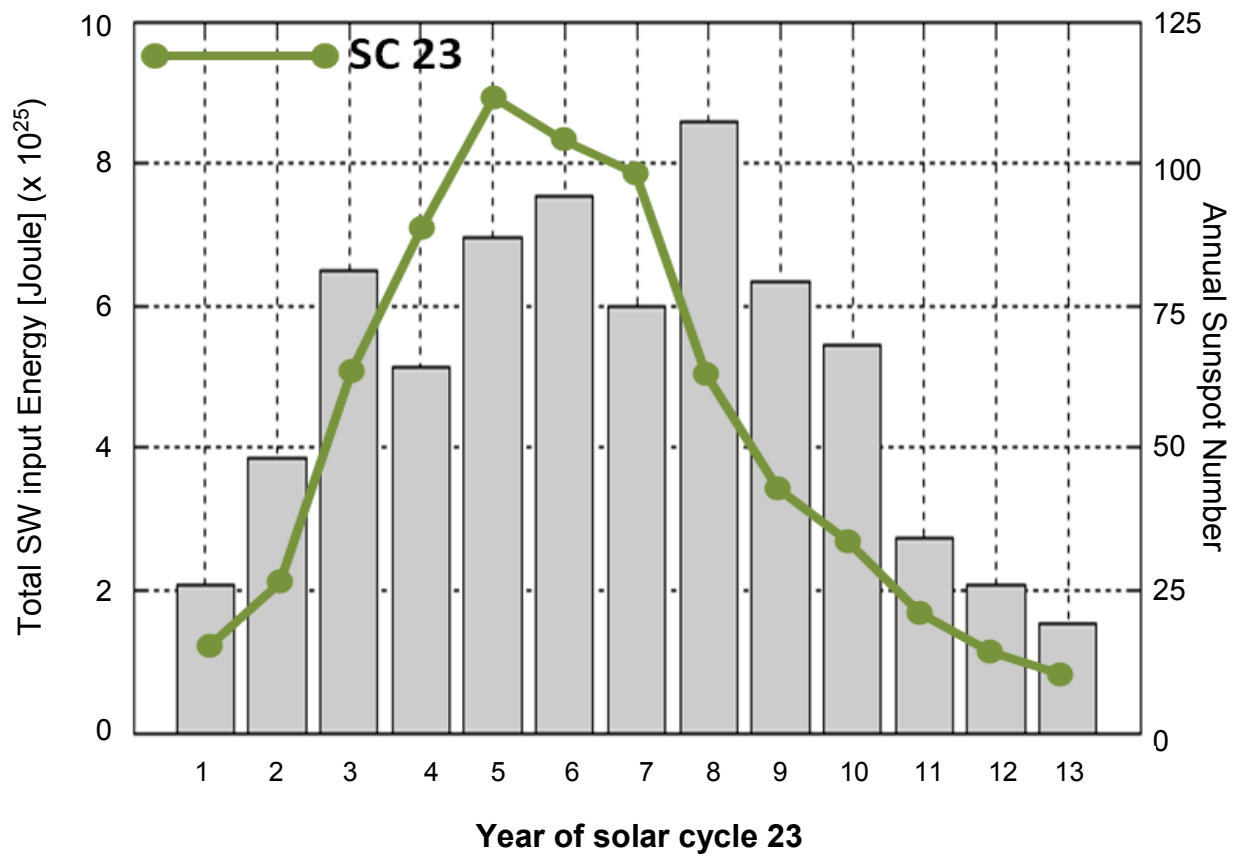


Figure 30: Yearly solar wind input energy during solar cycle 23

The relationship between earthquake released energy and solar wind energy input is examined in more detail by separating the earthquakes into shallow (epicenter depth < 40 km) and deep ones (epicenter depth > 40 km). Figures 31 and 32 show the variation of earthquake released energy and solar wind energy with sunspot number, for shallow and deep earthquakes, respectively. In both figures, Y-axis on the left panel represents the solar wind input energy and Y-axis on the right panel represents the amount of earthquake energy. Both parameters are plotted based on the sunspot number on the X-axis. From Figure 31, we can see the solar wind input energy is increasing when the sunspot number increase to the value around 63. Solar wind input after that keeps stable at the value above 3.2×10^{25} Joule during higher sunspot number (greater than 63). For earthquake energy, the trend shows a single peak at sunspot number 40 before dropped to below 0.25×10^{18} Joule at sunspot number greater than 63. For deeper depth earthquakes (40-100 km) as shown in Figure 32, the amount of earthquake energy shows a single peak at sunspot number around 15 before dropped to the value below than 3×10^{16} Joule at sunspot number greater than 20. As comparison, the value of earthquake energy released from earthquake at epicenter depth < 40 km is very high and dominating the total amount of earthquake energy released from epicenter depth less than 100 km. The highest amount of solar wind input energy and earthquake energy occurred during the mid-range of sunspot number, in between 40 to 65.

The similar result has been obtained by Odintsov et al., [2005] which found that, the maximum of earthquake energy released during the third year after sunspot maximum, where this is during the mid-range value of sunspot number. This is a good motivation for us to further analyze the physical mechanism which possibly connecting the solar wind input energy and seismic activity.

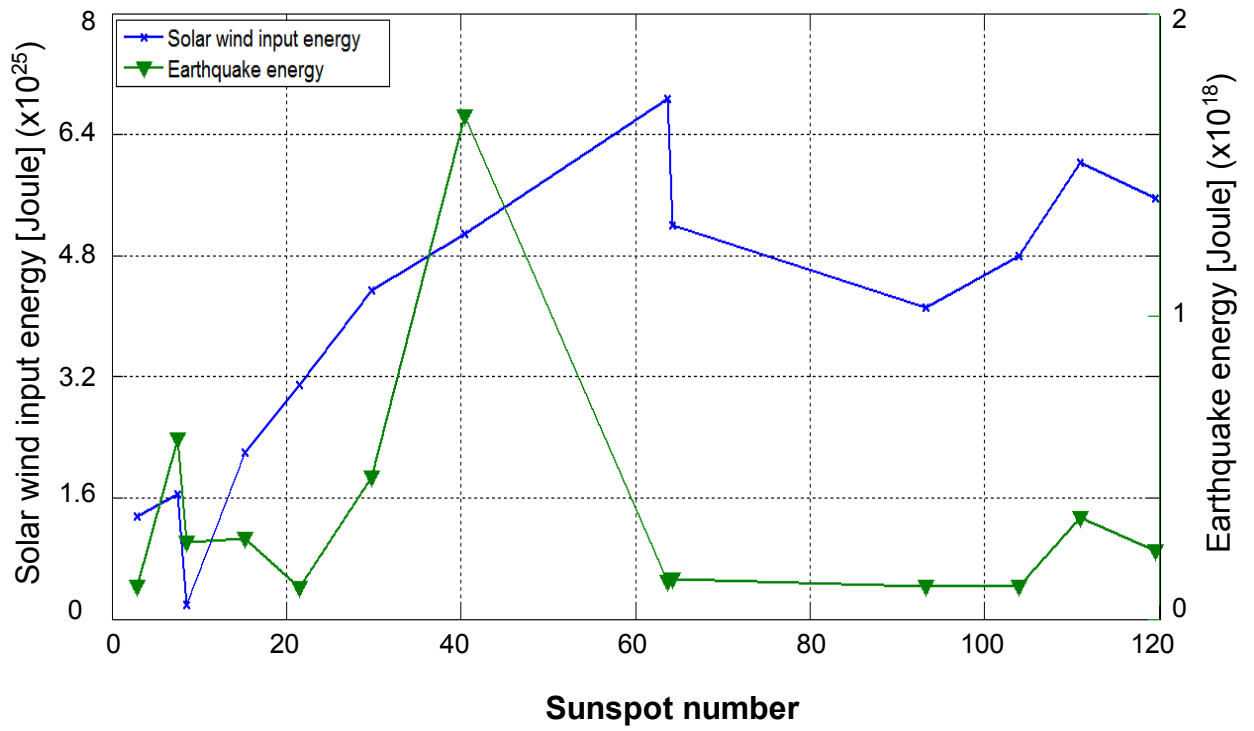


Figure 31: Solar wind input energy and earthquake released energy from epicenter depth < 40 km with respect to sunspot number

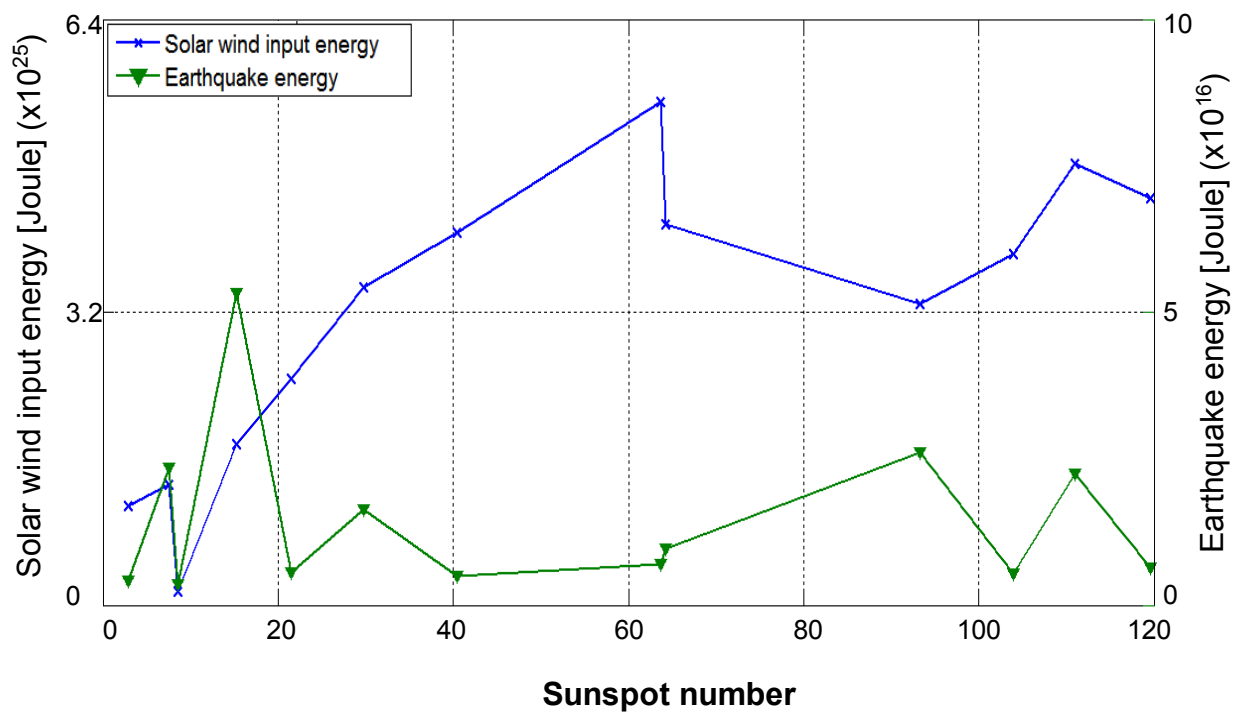


Figure 32: Solar wind input energy and earthquake released energy from epicenter depth 40-100 km with respect to sunspot number

To investigate the possible relationship between SW input energy and earthquake event, we have plotted Figure 33 which shows the amount of energy from (a) solar wind, and (b) global earthquake at lower magnitude range, 4.0 – 5.9 and (c) higher magnitude range, 6.0 – 9.9. The estimation of energy from the solar wind and earthquake events was done during the period of 5 to 25 March 2011. Within this period, in Figure 33(a), we have observed an abrupt increase in the amount of SW input energy on March 10 with the value around 8×10^{18} Joule. This is 8 times increment from the background average values. For earthquake energy released from lower range of magnitude as shown in Figure 33(b), the amount of energy increased suddenly on March 11, one day after the abrupt change of SW input energy. The maximum value recorded on this day is 2.4×10^{15} Joule. With the magnitude of 6.0 to 9.9 of earthquake as shown in Figure 33(c), a sudden increase of earthquake energy also occurred on 11 March, the same day of maximum earthquake energy released at lower magnitude. The maximum value recorded reached up to 5.2×10^{23} Joule. The main points can be raised here are:

- i. The amount of energy from solar wind is relatively big as compared to the energy released from the earthquakes of both magnitude ranges. Therefore, there is the possibility that SW input energy could be one of the energy sources for earthquake.
- ii. The variation of SW input energy observed during this period corresponds well with the amount of earthquake released energy from both magnitude ranges. The earthquake energy from both magnitudes ranges rise distinctly one day after the sudden increase of SW input energy. For reference, on 11 March, 2011, a mega earthquake with magnitude 9.1 occurred at Tohoku region, Japan.

The points mentioned above are our motivations to further analyze the possible correlation between solar wind and seismicity.

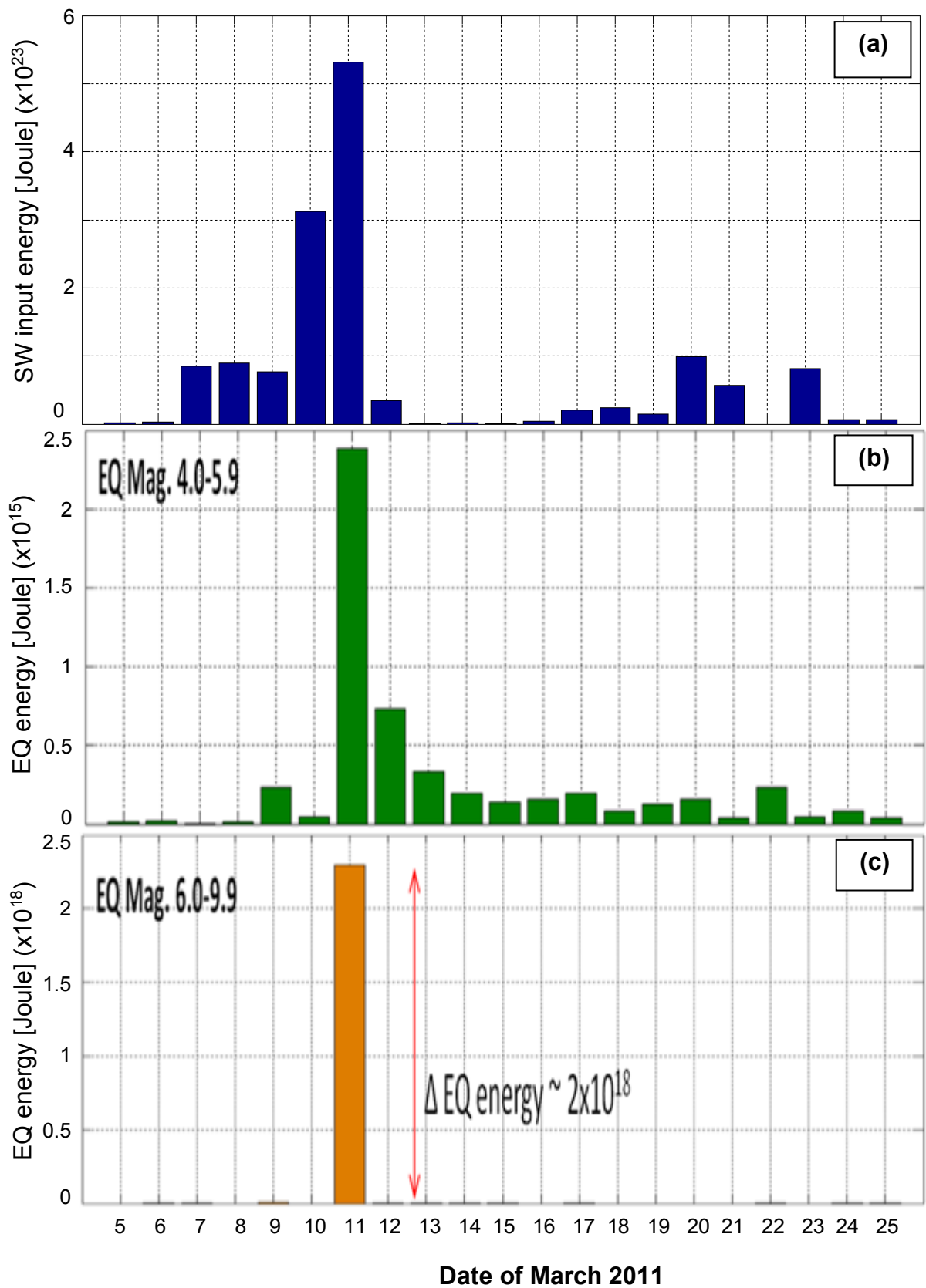


Figure 33: Comparison of energy from (a) solar wind, and (b) earthquake at lower magnitude range, 4.0 – 5.9 and (c) higher magnitude range, 6.0 – 9.9

Chapter 4

Discussion: Possible physical mechanism

In previous chapters, we have seen the results that show the possible relationship between solar activity and earthquake events. The question arises here is what is the physical mechanism that connects the solar and seismic activity? In the following sections, we try to discuss the possible physical mechanisms using observations.

4.1 Ultra Low Frequency (ULF) of magnetic pulsations (Pc)

Thus, electromagnetic waves (EM) in the ULF range extracted from ground observations are considered as 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 evidences of electromagnetic 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 electromagnetic fields of 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 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. The penetration depth increases with decreasing underground conductivity. Due to this reason ULF waves (geomagnetic pulsations, Pc 3–5 types) as mentioned earlier in Table 1 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 behavior of ground observed ULF fields.

To connect the solar activity 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 at north Japan and Langkawi (Malaysia); for earthquakes monitoring at north Sumatera.

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

For this study, we have examined the statistics of earthquake occurrences at different epicentre depths for both regions. Figure 34 and Figure 35 show the number of earthquakes at different epicenter depth in north Japan region during year 2005 and in north Sumatra region during year 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, Pc 5 range at period 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.

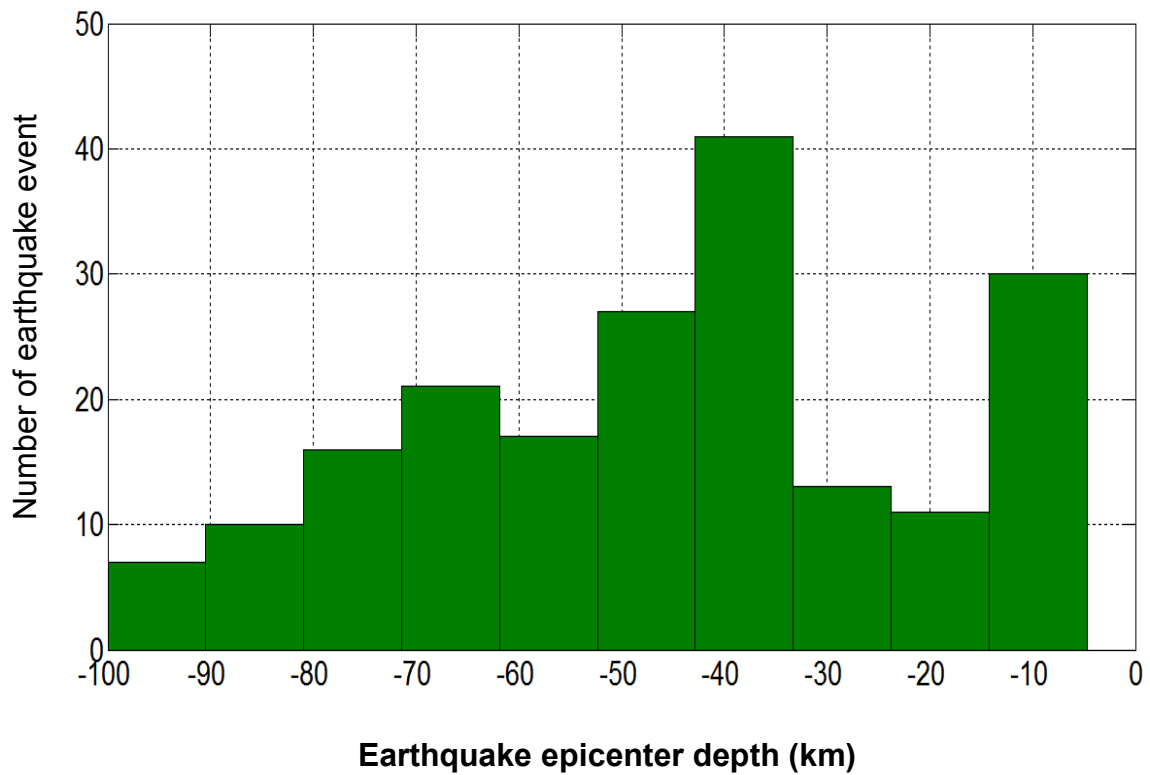


Figure 34: Epicenter depth of North Japan region earthquake for year 2005

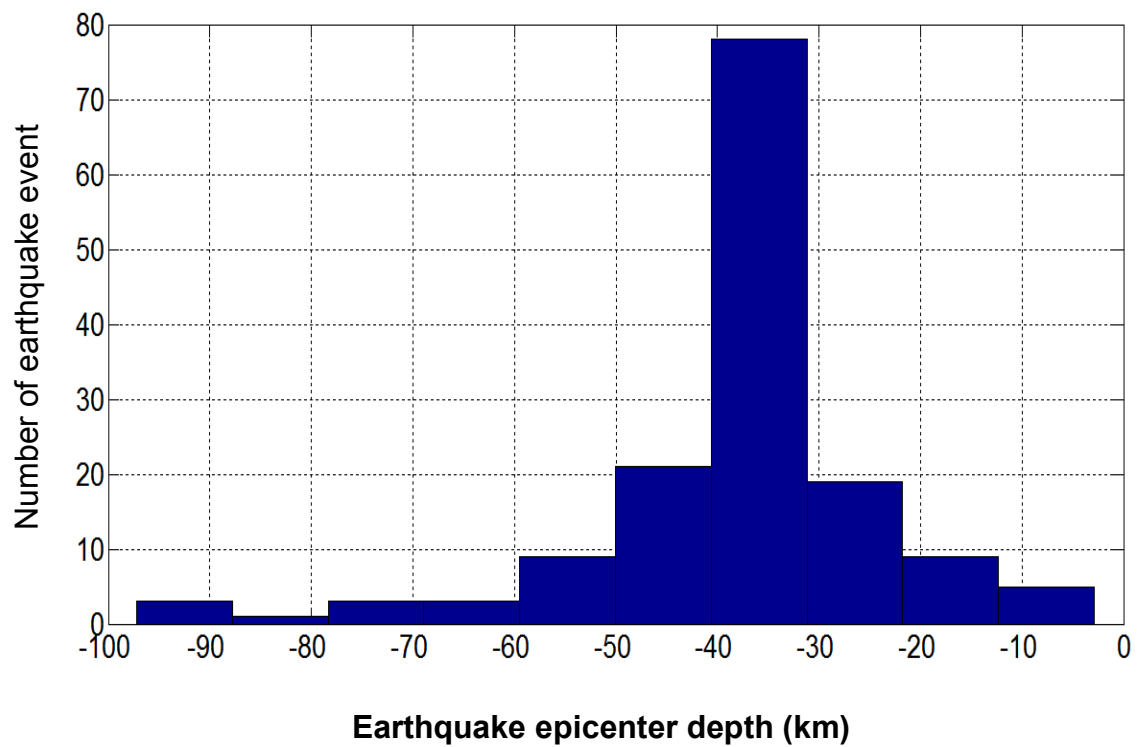


Figure 35: Epicenter depth of North Sumatra region earthquake for year 2010

4.1.1 North Japan region

We have analyzed 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 solar wind 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 earthquake.

In Figure 36(a), we can see the variation of solar wind 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 36(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 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 solar wind speed. This confirms the studies by previous researchers that Pc 5 is a good index for SW speed [Baker et al., 2003 and Rae et al., 2005].

Figure 36(c) shows the epicenter depth of earthquakes occurred during the same period. Comparing with Figure 31(b), we can see the number of earthquakes with epicenter depth of ~ 60 km follows closely the amplitude of Pc 5. This demonstrates the potential connection between the two.

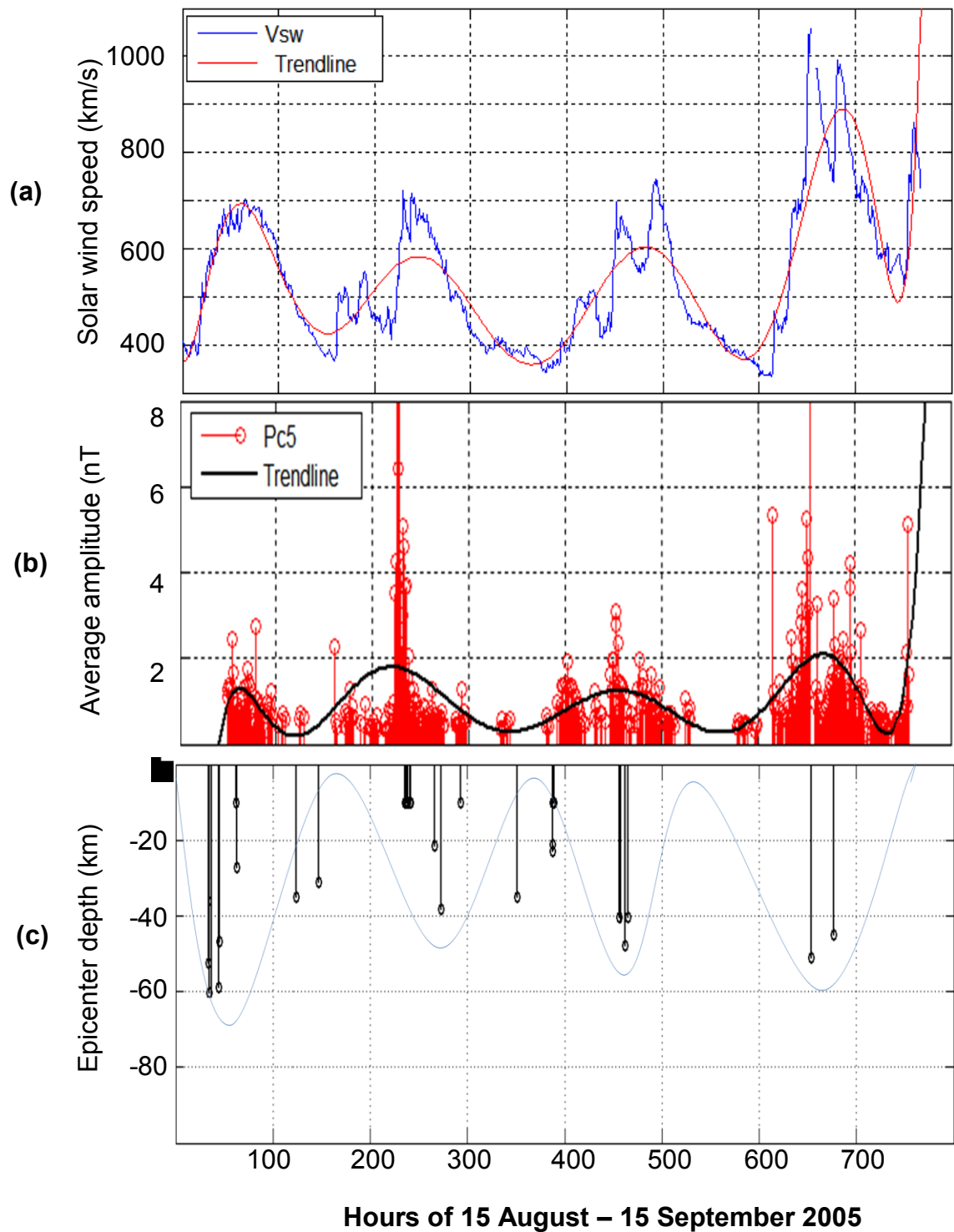


Figure 36: Variation of (a) solar wind speed, (b) amplitude of Pc 5 and (c) epicenter depth earthquake events from 15 August to 14 September 2005 for North Japan region.

4.1.2 North Sumatra region

For this region, we have done similar analysis to the north Japan region but in different time period to see the correspondence of geomagnetic pulsation Pc 5 and earthquake occurrences in Sumatra region. The observation of solar wind speed, geomagnetic pulsation Pc 5 and earthquake event shown in Figure 37(a), (b) and (c) respectively was done during 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 37(a), at first 100-hour of observation, the solar wind speed was 500 km/s before decreasing and increasing in the next 200-hour period. The solar wind 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 solar wind speed variation corresponds well with that of the geomagnetic pulsation Pc 5 as shown in Figure 37(b). Throughout the observation period, the average amplitude of geomagnetic pulsation Pc 5 is around 2 nT. However, several events of high Pc 5 amplitude at more than 2 nT were observed around 200-hour, the same period of solar wind 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 solar wind 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 37(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 3 observed parameters have a good correspondence in tendency. It can be summarized that during the enhancement of solar wind 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 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 solar wind 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 solar wind 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 solar wind speed control the occurrence and the amplitude of ground pulsations in the Pc 3 and Pc 4 range. Greenstadt et al., [1979] have observed positive correlations of magnetic pulsations Pc 3, Pc 4 and Pc 5 at Calgari and Leduc stations with solar wind speed.

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

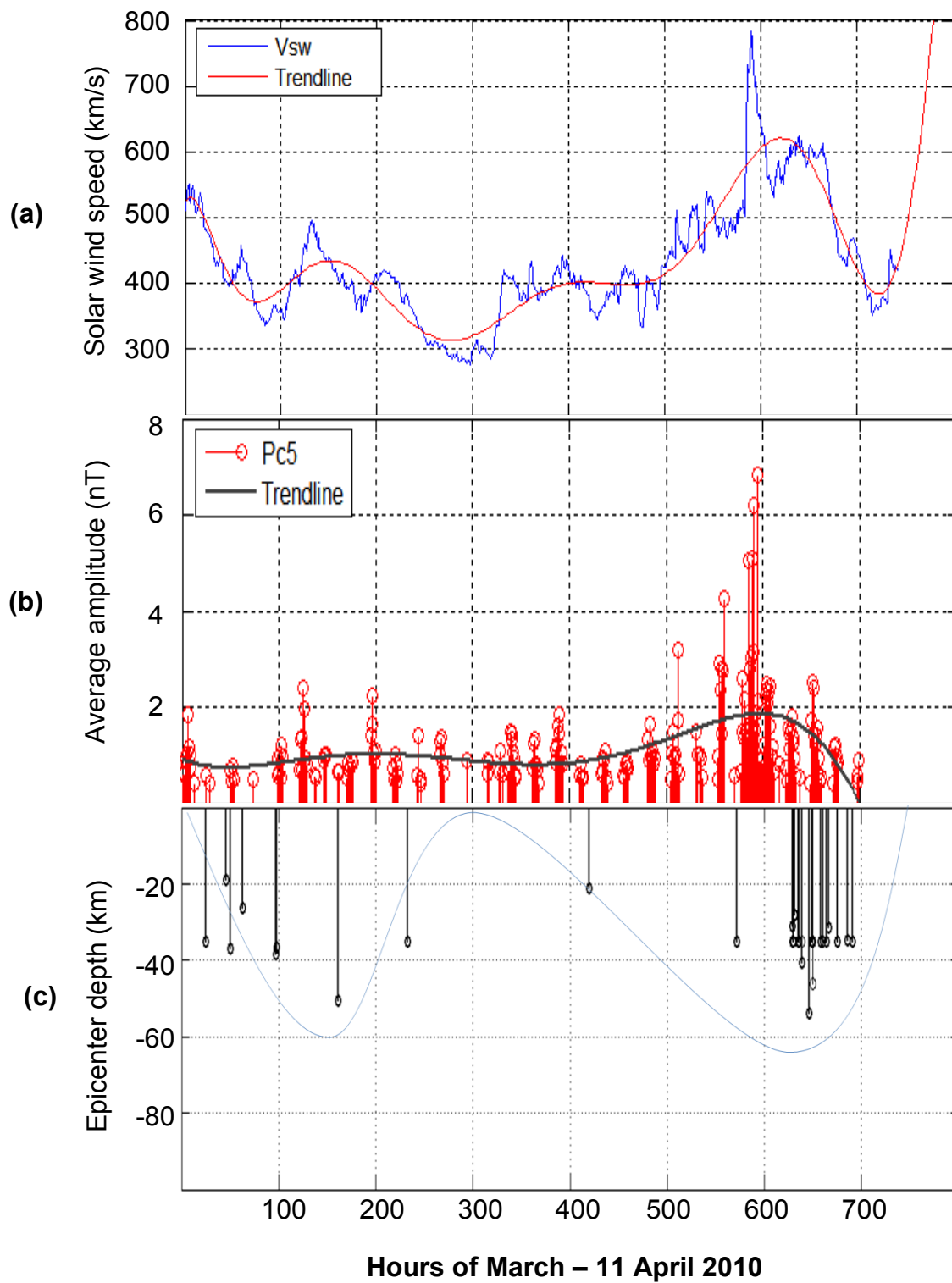


Figure 37: Variation of (a) solar wind speed, (b) amplitude of Pc 5 and (c) epicenter depth earthquake events from 12 March to 11 April 2010 for North Sumatra, Indonesia region.

4.2 Lorentz Force

Lorentz force is the total force exerted on a charged particle due to existing of electromagnetic field. From geophysical aspect, Lorentz force explains the piezomagnetic effect where this force is a manifestation of the effect due to the underground telluric currents on the magnetized earth's crust and upper mantle.

During high speed solar wind event, the solar wind input energy gives rise to large ionospheric current vortices above the sun-lit northern and southern hemispheres, which induce powerful currents in the Earth's crust and upper mantle. As Duma and Ruzhin, [2003] have pointed out these induced currents generate a torque which may play a role in triggering earthquakes.

A group of researchers from Laboratory of Pulse MHD Power System for Geophysics, Russia, has done a series of observations and experiments on the triggered earthquakes by injecting high power electromagnetic pulses of magneto hydro dynamic (MHD) generator into the earth [Tarasov, and Tarasova, 2004 and Zeigarnik et. al, 2007]. The observed earthquakes have increased nearly 70% several days after high power electromagnetic pulses with electric current 2.5 – 3.5 kA injected into the ground with 2 – 10 second duration through dipole electrodes of MHD over the Northern Tien Shan and Pamir regions, Russia.

This is similar to the case when we consider the source of high electromagnetic energy from the solar wind (eg: geomagnetic storm). The basic question here is whether the electromagnetic process may provide enough energy for earthquake. Further studies by Duma and Vilardo, [1997] and Duma and Ruzhin, [2002], revealed that the induced telluric currents in the conductive Earth's lithosphere play the dominant role. In presence of the Earth's main magnetic field, telluric currents generate Lorentz forces which act on the lithosphere.

A schematic sketch of induced Sq current system in the Earth's interior was presented by Matsushita, [1968], as shown in Figure 38. The Sq variation induces currents (*telluric currents*) in the conducting crust, which are formed by current vortex in the northern hemisphere and in the southern hemisphere. The current pattern is very similar to the external Sq current vortex in the ionosphere. In addition to that, the empirical study by Yamazaki et al., [2011], has shown that the total induced underground current is 45% of the ionospheric current. By referring to these facts, it is possible to estimate the induced underground current by external Sq current system.

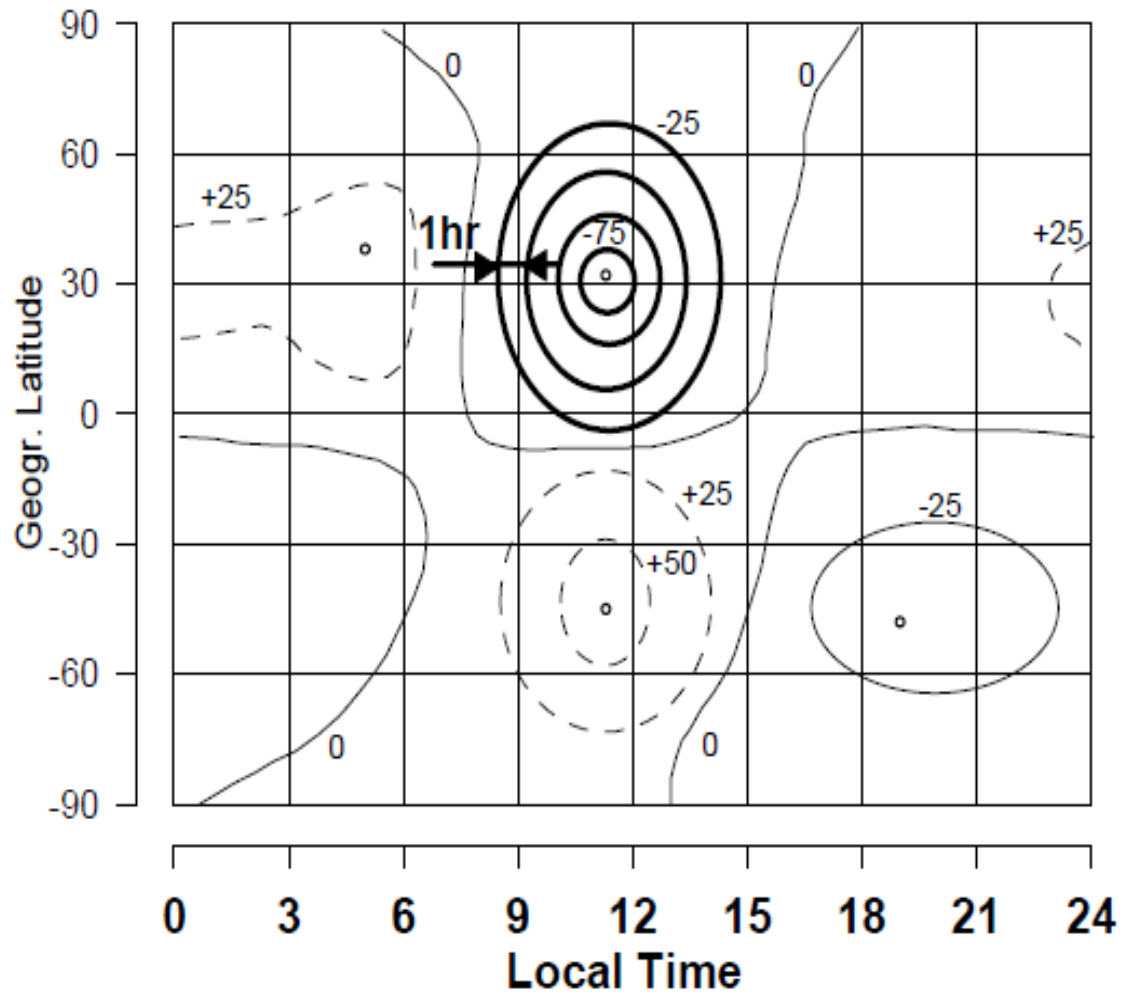


Figure 38: Schematic sketch of the average induced Sq current system in the lithosphere [Matsushita, 1968]

To connect the solar activity with seismicity, we are considering electro-mechanical force during disturbed period (high solar wind input energy) as one of the possible physical mechanism. From the electrodynamics principle, the circular electric currents that flow in magnetic field will generate magnetic moment, MM, and possible to induce mechanical torque into underground subduction zone before possibly triggering the earthquakes. The magnetic moment can be calculated from equation (4):

$$\mathbf{MM} = \mu_o * I * (D^2 * (\pi/4)) \quad (4)$$

Where;

MM = Magnetic Moment [Am^2]

Permeability of free space, $\mu_o = 4\pi 10^{-7} \text{ Vs/Am}$

I = Electric current [A]

D = Diameter of enclosed area [m]

Torque, T on the conductive layer in which the ring currents flow can be calculated from equation (5) as the vector product of magnetic moment and local geomagnetic component:

$$\mathbf{T} = \mathbf{MM} \times \mathbf{H} \quad (5)$$

Where;

T = Torque [Joule or VAs]

H = Horizontal component of geomagnetic intensity, [A/m]

By considering the underground induced Sq current, it is possible to estimate the total amount of force; F in the presence of geomagnetic field, B from formula (6):

$$\mathbf{F} = \int \mathbf{J} \times \mathbf{H} \quad (6)$$

Where;

F = Force [N]

J = Induced underground current (telluric current) [A]

H = Geomagnetic field [nT]

Figure 39 shows the electromagnetic model by illustrating how a horizontal current loop or radius r , flowing through the horizontal component H of the Earth's main field, will generate a magnetic moment MM in the vertical direction and a torque T [G. Duma and Y. Ruzhin, 2003]. Any current loop of intensity I in the vortices, flowing in the crust and through the horizontal (H) and vertical (Z) components of the main geomagnetic field, will respectively generate vertical and horizontal forces against the crustal rocks and structures.

In areas with significant lateral conductivity variations, such as in the regional faulting structures, vertical electric currents flowing through the horizontal and vertical components of the main field may generate additional effects. In consequence, the diurnal geomagnetic variation exerts on the crust a small albeit finite stress (*surcharge*), which is added to the tectonic stress and may affect the state of metastable faults.

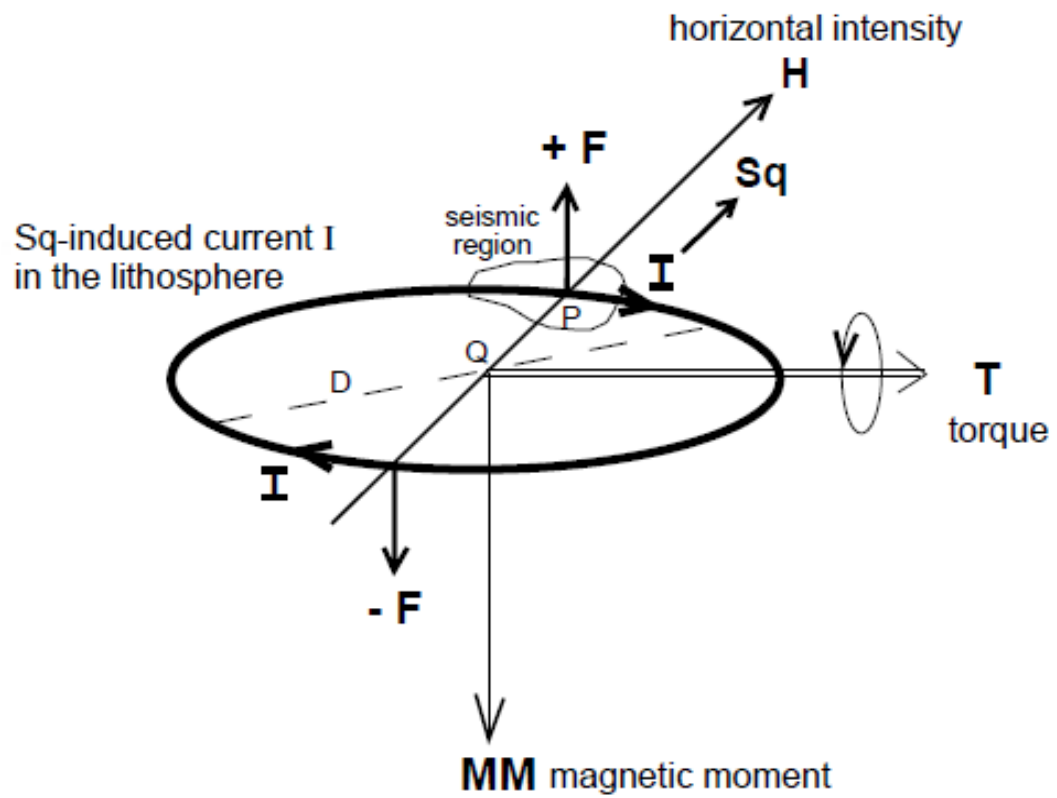


Figure 39: Electromagnetic model of MM concept with regards to Sq-induced current and horizontal component of earth's magnetic field [Duma and Ruzhin, 2003]

According to Akasofu, [1981], and Tsurutani and Gonzalez, [1997], during the period of high input electromagnetic energy, the amplitude of ionospheric current will also be enhanced. The establishment of magnetometer network array by MAGDAS/CPMN system is also helpful in monitoring the global ionospheric current system.

For instance, we have observed the typical ionospheric current during high solar wind input energy on 22 August 2005. Figure 40 shows the observation of solar wind input energy variation from 20 to 22 August 2005. From this figure, we can see an abrupt increase of solar wind input energy on 21 August and reached its peak on 22 August. The increment is around 9 folds as compared to the background level. Observation of the ionospheric current at Ashibetsu station during low solar wind input energy on 20 August (blue line) and high solar wind input energy on 22 August (green line) are show in Figure 41. Strong enhancement of ionospheric current is clearly observed on 22 August, the same day where the increased of solar wind input energy observed.

In order to quantify the variations of torque and forces involved in the electromagnetic model of MM, we have tabulated the estimation of torque and force generated during different conditions of solar wind input energy in Table 3. It may easily be shown that by assuming the MAGDAS Ashibetsu (ASB) magnetometer station as reference station, the distance between the center of Sq-current vortex and ASB station, $D \approx 3000$ km, the value of horizontal component of magnetic field, $H \approx 27,000$ nT and the estimated induced telluric current during high solar wind input energy (45% from ionospheric current [Yamazaki et al., 2011], $I \approx 54$ kA, the estimated torque, T supplied to the earth's crust is 5.1×10^{12} Joule, approximately equivalent to an earthquake of moment magnitude 5.4 Richter scale. One can see

clearly that during higher solar wind input energy, the estimated induced telluric current also increases, therefore producing higher force to the earth's crust.

It is therefore clear that the amount of energy transferred from the Ionosphere to the Lithosphere and dissipated in the form of mechanical deformation is significant. Accordingly, the probability that this energy may trigger earthquakes should also be significant.

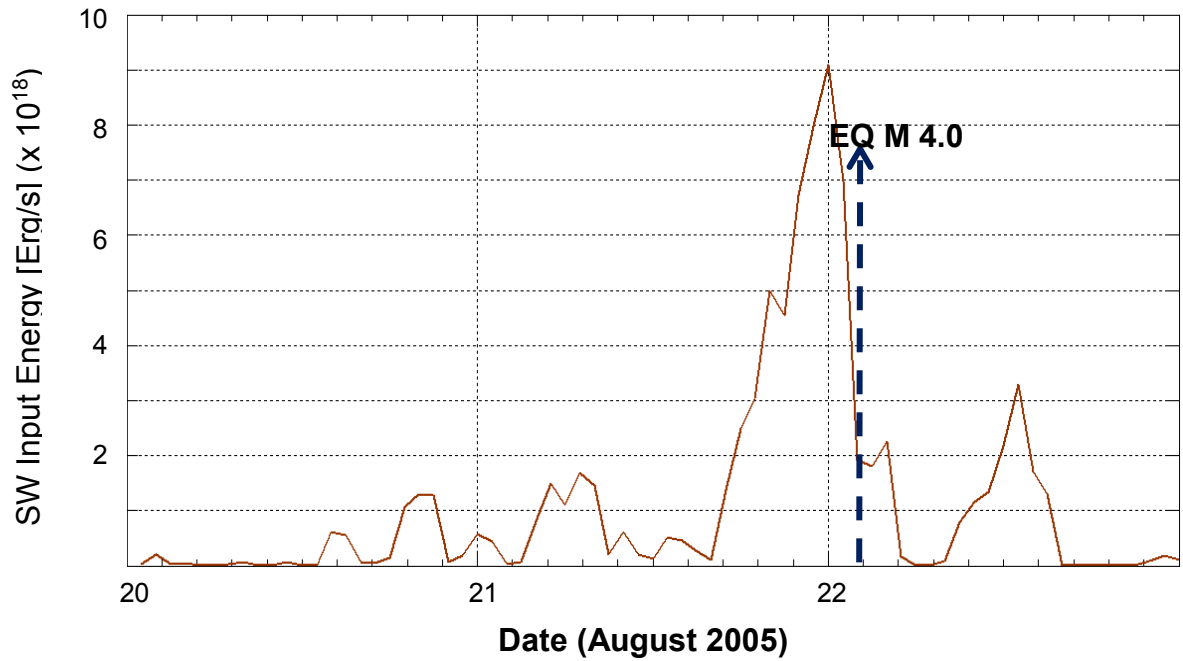


Figure 40: Observation result of solar wind input energy variation from 20 to 22 August 2005

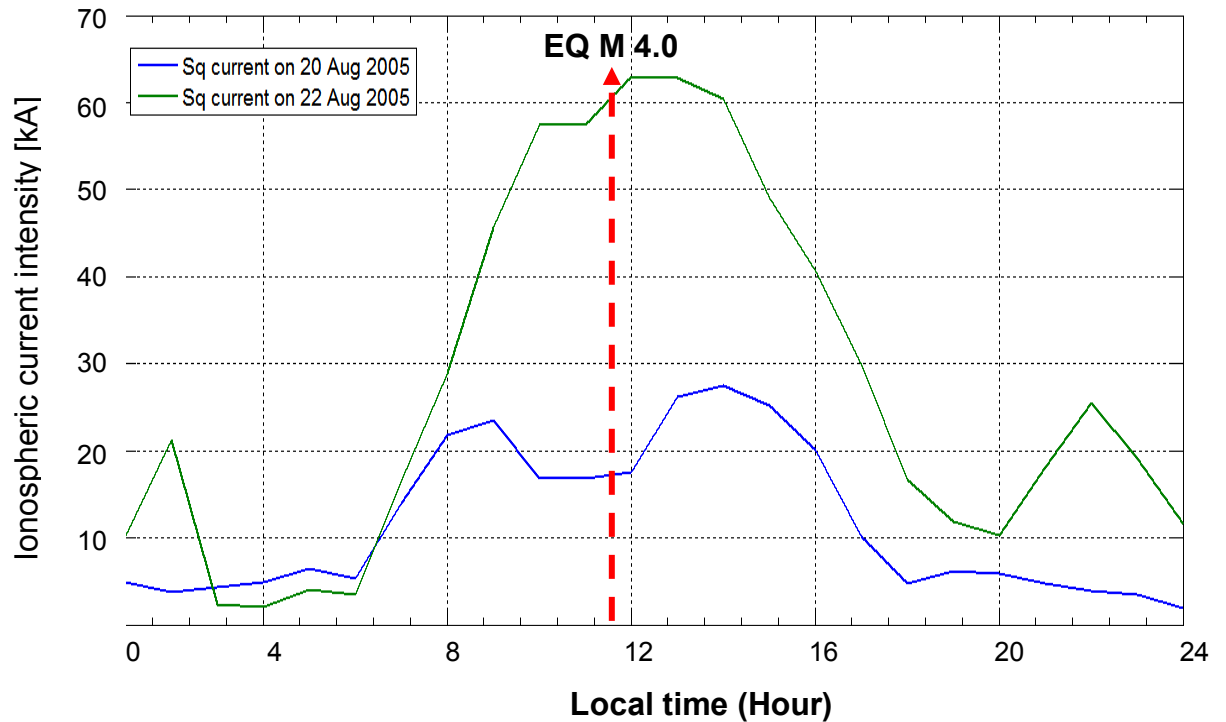


Figure 41: Observations of ionospheric current during low solar wind input energy on 20 August (blue line) and high solar wind input energy on 22 August (green line) at Ashibetsu station, Japan

Table 3: Estimation of torque and force at different solar wind input energy

SW input energy [Erg/s]	Average ionospheric current [kA] (Induced I)	Magnetic moment [10 ¹⁰ Am ²]	Torque [10 ¹² Joule]	Force, F [kNm ⁻²]	Equivalent magnitude (Log E = 4.7 + 1.5M)
$\varepsilon < 10^{17}$	40 (18)	6.4	1.7	486	5.0
$\varepsilon: 10^{17} \sim 10^{18}$	80 (36)	12.8	3.5	972	5.2
$\varepsilon > 10^{18}$	120 (54)	19	5.1	1500	5.4

By assuming:

5 km is the height of ionospheric current

200 km is the width of ionospheric current

Model calculations reveal that the induced currents may involve an unexpected high amount of energy, comparable to the earthquake energy itself. This result strengthens the hypothesis of a powerful trigger mechanism due to the induced telluric currents.

Chapter 5

Summary and 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 prolonged period and most recent solar cycles. Various solar wind parameters are considered, which include the solar wind speed, solar wind dynamic pressure and solar wind input energy. In our attempts to explain the physical mechanism of solar activity and seismicity, we are focussing on geomagnetic pulsations extracted from the ground magnetometer and the effect of Lorentz force.

We can summarize the results of this study as follows:

1. Variation of earthquake occurrence with solar cycle

We have re-examined the relationship between global earthquake event and solar cycle with longer time period covering the most recent solar cycles which are from solar cycle 20 to 23. In the analysis, the global earthquake events were categorized at each magnitude from magnitude 4.0 to 9.9 Richter scale. This is important to precisely identify the pattern of different earthquake magnitude with solar cycle. The amount of energy from global earthquake also has been analyzed. We also examined the energy released from local earthquake events in the area of actively seismic regions which are Japan and Sumatra (Indonesia)

regions during the same period with global earthquake analysis. From our observation, earthquakes of all magnitude for both global and local events tend to occur more frequently during descending solar cycles. The seismic region located in low latitude region (Sumatra) has 1-year delay between the maximum amount of energy released and the descending phase of solar cycle. These results confirmed the studies by previous researchers.

2. Relationship of earthquake with solar wind speed

The analysis of earthquake events with high speed solar wind events has been done by previous researchers but only at shorter time period (Odintsov et al., 2006 - period of analysis: 1973 to 2000) and small number of high speed solar wind event (Gousheva et al., 2003). In our study, we have analyzed the earthquake event with high speed solar wind during longer time period from year 1964 to 2008 with total number of high speed solar wind event 1603 cases. The results show the high speed solar wind tends to trigger more earthquakes 1 day after its arrival. This result agrees with studies by previous researchers as mentioned earlier.

3. Relationship of earthquake with solar wind dynamic pressure

The analysis of solar wind dynamic pressure with earthquake events is a new investigation we have carried out. The original idea was first proposed theoretically by Tavares and Azevedo, [2011], but without any statistical analysis. Our analyses show that the solar wind dynamic pressure corresponds well with earthquake event where around the onset time of high solar wind dynamic pressure, more earthquake events have been observed.

4. Relationship of earthquakes with solar wind input energy

As solar wind input energy is a measurement of the amount of the energy penetrated from the solar wind into the earth's magnetosphere, it is an important parameter for investigations on solar wind impact on the earth. The estimated solar wind input energy is big enough to be one of the energy sources for earthquake event. The observation on the significant earthquake events; Tohoku earthquake also shows the enhancement of solar wind input energy correspond well with the earthquake events. However, to conclude the possible relationship between solar wind input energy and earthquake events needs a further analysis and evaluation considering more statistical analysis.

Another focus of our study is to explore the possible physical mechanisms connecting solar activity and seismicity. We have referred several studies by previous researchers regarding to this matter. We have considered the following aspects as promising physical mechanisms connecting solar activity and seismicity:

1. Ultra Low Frequency (ULF) of geomagnetic pulsations

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 the 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.

2. Lorentz Force

Gerald Duma, and his co-researcher, Ruzhin first introduced clearly the physical mechanism to relate solar activity and earthquake event by introducing the possible influence of Lorentz force into the lithosphere in his work [Duma and Ruzhin, 2003]. For this study, we are examined the effect of Lorentz force from different aspect. We consider different conditions of solar wind input energy as controlling factor to the amount of induced telluric currents in the earth's crust. From our analysis, the higher amount of solar wind input energy will induce higher telluric current into the earth's crust and significantly increase the force on the lithosphere which may affect the state of metastable faults and could possibly trigger the seismic activity.

Significance and recommendation

Our study addresses the possible relationship between solar wind parameters and seismicity. Even though solar activity and seismicity coupling have been reported for centuries and from every tectonically active region of the world, many researchers in the geophysical community remain deeply sceptical towards most earthquake precursor. This could be due to the fact that the reported phenomena are still ambiguous and lack of satisfactory explanation. Therefore, extensive research on the perspective of sun – earth coupling mechanism should be done actively. This surely warrants further analysis and evaluation involving extension of observational

data and also some advanced statistical analysis method to ensure the relationship of solar activity and seismicity to be comprehensively explained.

Acknowledgement

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Mohamad Huzaimy Jusoh

Fukuoka, 1 Ramadhan, 1434 (July 2013)

References

- Anagnostopoulos, G. and Papandreou, A., Space conditions during a month of a sequence of six $M > 6.8$ earthquakes ending with the tsunami of 26 December 2004, *Natural Hazards and Earth System Sciences*, volume 12, pp. 1551–1559, 2012
- Akasofu, S. I., Energy coupling between the solar wind and the magnetosphere, *Space Science Reviews*, volume 28, pp. 121-190, 1981
- Axford, W. and Hines, C. O., A Unifying Theory of High-Latitude Geophysical Phenomena and Geomagnetic Storms, *Canadian Journal of Physics*, Volume 39 (10), 1961
- Baker, N. D., Introduction to Space Weather, *Lecture Notes in Physics*, Volume 656, pp. 993–1020, 2005
- Belov, S. V., Shestopalov, I. P. and Kharin, E. P., On the relation between endogenic activity of the earth and solar and geomagnetic activity, *Doklady Earth Sciences*, pp. 1142-1145, 2009
- Boatwright, J., Seismic estimates of stress release: *Journal of Geophysical Research*, volume 89, pp. 6961-6968, 1984
- Boudouridis, A., Lyons, L. R., Zesta, E. and Ruohoniemi, J. M., Dayside reconnection enhancement resulting from a solar wind dynamic pressure increase, *Journal of Geophysical Research*, Issue A6, 2007
- Choi, C.-R., Kim, K.-C., Lee, D.-Y., Kim, J.-H., and Lee, E., Statistical Characteristics of Solar Wind Dynamic Pressure Enhancements During Geomagnetic Storms, *Journal of Astronomy and Space Science*, volume 25(2), pp. 113–128, 2008
- Deborah Kilb, Joan Gomberg, and Paul Bodin, Triggering of earthquake aftershocks by dynamic stresses, *Letters to Nature*, volume 408, pp. 570-574, 2000

- Duma, G. and Ruzhin, Y., Diurnal changes of earthquake activity and geomagnetic Sq-variations, *Natural Hazards and Earth System Science*, volume 3, pp.171-177, 2003
- Dungey, J. W., Interplanetary Magnetic Field and the Auroral Zones, *Physical Review Letters*, volume 6, pp. 47-48, 1961
- Fraser-Smith, A. C., Bernardi, A., McGill, P. R., Ladd, M. E., Helliwell, R. A. and Villard, O. G Jr., Low-frequency magnetic measurements near the epicenter of the Ms 7.1 Loma Prieta earthquake, *Geophysical Research Letter*, volume 17, pp. 1465-1468, 1990
- Gousheva, M. N., Georgieva, K. Y., Kirov, B. B., Atanasov, D., On the relation between solar activity and seismicity, *International Conference on. Proceedings of Recent Advances in Space Technologies, (RAST '03) 2003*, pp. 236-240, 2003
- Greenstadt, E. W. and Olson, J. V., A contribution to ULF activity in the Pc 3-4 range correlated with IMF radial orientation, *Journal of Geophysical Research*, volume 82, pp. 4991–4996, 1977
- Greenstadt, E. W., Olson, J. V., Loewen, P. D., Singer, H. J. and Russell C. T., Correlation of Pc3, 4 and 5 Activity with Solar Wind Speed, *Journal of Geophysical Research*, volume 84, pp. 6694-6696, 1979
- Gregory, J. Baker, Eric, Donovan, F., and Brian J. Jackel, A comprehensive survey of auroral latitude Pc5 pulsation characteristics, *Journal of Geophysical Research*, volume 108, 2003
- Gupta, V. and Badruddin, High speed solar wind streams during 1996 – 2007: Sources, statistical distribution, and plasma/field properties, *Solar Physics*, pp. 165-188, 2010

- Han Yanben, Guo Zengjian, Wu Jinbing and Ma Lihua, Possible triggering of solar activity to big earthquakes ($M_s \geq 8$) in faults with near west-east strike in China, Science in China Ser. G Physics, Mechanics and Astronomy, pp. 173-181, 2004
- Hayakawa, M., Molchanov, O. A., Ondoh, T., and Kawai, E.: The precursory signature effect of the Kobe earthquake on VLF subionospheric signals, J. Comm. Res. Lab., Tokyo, volume 43, pp. 169–180, 1996
- Hayakawa, M. and Molchanov, O. A. Editors, Seismo Electromagnetics: Lithosphere – Atmosphere – Ionosphere Coupling, TERRAPUB, pp. 477, 2002
- Hayakawa, M. and O. A., Molchanov, Seismo-electromagnetics as a new field of radiophysics: Electromagnetic phenomena associated with earthquakes, Radio Science Bulletin, volume 320, pp. 8–17, 2007
- Hayakawa, M., Ito, T. and Smirnova, N., Fractal analysis of ULF geomagnetic data associated with the Guam earthquake on August 8, 1993. Geophysical Research Letter, volume 26, pp. 2797–2800, 1999
- Hiroo Kanamori, Magnitude scale and quantification of earthquakes, Tectonophysics, Elsevier Scientific, pp. 185-199, 1983
- Jakubcova, I., and Pick, M., Correlation between solar motion, earthquakes and other geophysical phenomena, Annals Geophysics, volume 5(B), pp. 135- 141, 1987
- John F. Simpson, Solar Activity as a Triggering Mechanism for Earthquakes, Earth and Planetary Science Letter 3 pp. 417-425, 1967
- Kagan, Y. Y., Seismic moment distribution, Geophysics Journal, volume 106, pp. 123-134, 1991
- Kanamori, H., The Energy Release in Great Earthquakes, Journal of Geophysical Research, volume 82, pp. 2981- 2987, 1977

- Khain, V. E and Khalilov, E. N, About Possible influence of solar activity upon seismic and volcanic activities: long-term forecast, Transactions of the International Academy of Science H&E, pp. 217-240, 2007
- Kopytenko, Y.A., Matiashvili, T.G., Voronov, P. M., Kopytenko, E. A. and Molchanov, O. A., Detection of ultra-low frequency emissions connected with the Spitak earthquake and its aftershock activity, based on geomagnetic pulsations data at Dusheti and Vardzia observatories, Physics Earth Planet, volume 77, pp. 85-95, 1993
- Lanzerotti, L. J., Pipelines and Space Weather, Space Weather, volume 8, 2010
- Lee, D.-Y., L. R. Lyons and G. D. Reeves (2005), Comparison of geosynchronous energetic particle flux responses to solar wind dynamic pressure enhancements and substorms, Journal of Geophysical Research, volume 110, Issue A9, 2005
- Lee, D.-Y., Lyons, L. R. and Yumoto, K., Sawtooth oscillations directly driven by solar wind dynamic pressure enhancements, Journal of Geophysical Research, volume 109, 2004
- Lee, D.-Y., Ohtani, S., Brandt, P. C. and Lyons, L. R., Energetic neutral atom response to solar wind dynamic pressure enhancements, Journal of Geophysical Research, volume 112, Issue A9, 2007
- Lyatsky W., Sonya Lyatskaya and Arjun Tan, A coupling function for solar wind effect on geomagnetic activity, Geophysical Research Letter, 2007
- Lyons, L. R., Lee, D.-Y., Wang, C.-P., & Mende, S., Dynamic pressure enhancements as a cause of large-scale stormtime substorms, Journal of Geophysical Research , 2008
- Maris, G. and Maris., High speed plasma streams (HSPS) in solar wind during the 22-year solar magnetic cycle (II), Solar Researches in the South-Eastern European Countries: Present and Perspectives, pp. 61-67, 2001

- Mavromichalaki, H., and Vassilaki, A., Fast plasma streams recorded near the earth during 1985-1996, *Solar Physics*, pp. 181-200, 1998
- Matsushita, S., Solar quiet and lunar daily variation fields, *Physics of Geomagnetic Phenomena*, International Geophysics Series, volume 1, 1968
- Molchanov, O. A., and Hayakawa, M., Seismo-electromagnetics and Related Phenomena: History and Latest Results, TERRAPUB, Tokyo, pp. 189, 2008
- Molchanov, O. A., Yu. A. Kopytenko, Voronov, P. M., Kopytenko, E. A., Matiasvili, T. G., Fraser-Smith, A. C. and Bernardi, A., Results of ULF Magnetic field measurements near the epicenters of the Spitak ($M_s=6.9$) and Loma Prieta ($M_s=7.1$) earthquakes: comparative analysis, *Geophysical Research Letter*, volume 19, pp. 1495-1498, 1992
- Molchanov, O. A. and Hayakawa, M., Generation of ULF electromagnetic emissions by micro fracturing, *Geophysical Research Letter*, volume 22, pp. 3091–3094, 1995
- Mukherjee, S. and Mukherjee, A., Change in magnetic field: an early warning system to understand seismotectonics, 1st Potsdam Thinkshop Poster Proceedings, pp. 139–142, 2002
- Nikolaev, A. V. and Nikolaev, V. A., Earth Tides Triggering of Earthquakes, *Continental Earthquakes*, Beijing, Seismological Press, pp. 319-327, 1993
- Odintsov S., Boyarchuk, K., Georgiva, K., Kirov B. and Atanasov, D., Long-period trends in global seismic and geomagnetic activity and their relation to solar activity, *Physics and Chemistry of the Earth*, pp. 88-93, 2006
- Odintsov, S. D., Ivanov-Kholodnyi, G. S. and Georgieva, K., Solar Activity and Global Seismicity of the Earth, *Bulletin of the Russian Academy of Sciences: Physics*, volume 71, pp. 593–595, 2007

- Paul, P. and Akasofu, S. I., A study of geomagnetic storms, *Geophysical Journal of Royal Astronomy Society*, volume 54, pp. 547-573, 1978
- Prikryl, P., Muldrew, D. B., and Sofko, G. J., High-speed solar wind, auroral electrojets and atmospheric gravity waves: a link to the earth's atmosphere, In press in *Proceedings of the International Solar Cycle Studies Symposium 2003: Solar Variability as an Input to the Earth Environment*, June 23-28, 2003, Tatranska Lomnica, Slovakia, 2003
- 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, A., Evolution and characteristics of global Pc5 ULF waves during a high solar wind speed interval, *Journal of Geophysical Research*, volume 11, issue A12, 2005
- Rozhnoi, A., Solovieva, Molchanov, M. S., and Hayakawa, M., Middle latitude LF (40 kHz) phase variations associated with earthquakes for quiet and disturbed geomagnetic conditions, *Physics and Chemistry of the Earth*, volume 29, pp. 589–598, 2004
- Russell, C. T., Ginskey, M., and Petrinec, S. M., Sudden impulses at low-latitude stations: Steady state response for northward interplanetary magnetic field, *Journal of Geophysical Research*, pp. 253-261, 1994
- Saito, T., A new index of geomagnetic pulsation and its relation to solar M-regions, *Report on Ionospheric Space Research, Japan*, volume 18, pp. 260–274, 1964
- Sasorova, E. V. and Levin, B. W., Seismotectonics and Earth Tides, *Russian Journal of Pacific Geology*, volume 6, pp. 70–77, 2012
- Shi, Y., Zesta, E., Lyons, L. R., Yumoto, K., & Kitamura, K., Statistical study of effect of solar wind dynamic pressure enhancements on dawn-to-dusk ring current asymmetry, *Journal of Geophysical Research*, Volume 111, Issue A10, 2006

- Sieh, K. and Natawidjaja, D, Neotectonics of the Sumatran fault, Indonesia, *Journal of Geophysical Research*, volume 105, pp. 28295-28326, 2000
- Singer, H. J., Russell, C. T., Kivelson, M. G., Greenstadt, E. W., and Olson, J. V., Evidence for control of Pc 3,4 magnetic pulsations by solar wind velocity, *Geophysical Research Letter*, volume 4, pp. 377–380, 1977
- Sytinskii, A. D., Influence of interplanetary disturbances on the seismicity and atmosphere of the earth, *Geomagnetic Aeronautics*, pp. 138-141, 1997
- Sytinskii, A. D., On the relation between earthquakes and activity, *Fizika Zemli*, volume 2, pp. 13-30, 1989
- Sytinskii, A. D., Recent tectonic Movements as Evidence of the Solar Activity, *Geomagnetic Aeronomy*, volume 3, pp. 148-156, 1963
- Tsurutani, B. T., and Gonzalez, W. D., The interplanetary causes of magnetic storms: A review, *Magnetic storms, Geophysics Monograph*, pp. 77, 1997
- Wallace H. Campbell, *Introduction to Geomagnetic Fields*, Cambridge University Press, 2003
- Wolfe, A., Dependence of mid-latitude hydromagnetic energy spectra on solar wind speed and interplanetary magnetic field direction, *Journal of Geophysical Research*, volume 85, pp. 5977–5982, 1980
- Wolfe, A., Meloni, A., Lanzerotti, L. J., and MacLennan, C. G., Dependence of hydromagnetic energy spectra near L=2 and L=3 on upstream solar wind parameters, *Journal of Geophysical Research*, volume 90, pp. 5117– 5131, 1985
- Yumoto, K and STPP Sub-Committee, International Heliophysical Year activities in Japan *Data Science Journal*, volume 8, pp. 14–23, 2009
- Yumoto, K and the 210⁰MM magnetic observation group, The STEP 210⁰ magnetic meridian project, *Journal of Geomagnetic and Geoelectricity*, volume 48, pp. 1297–1309, 1996

- Yumoto, K., and the MAGDAS Group, MAGDAS project and its application for space weather, *Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects*, Edited by N. Gopalswamy and A. Bhattacharyya, pp. 399-405, 2006
- 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., Ehora, R., and Servando, N., A new ULF wave analysis for Seismo-Electromagnetics using CPMN/MAGDAS data, *Physics and Chemistry of the Earth*, 360-366, 2009
- Zeigarnik, V. A., Novikov, V. A., Avagimov, A. A., Tarasov, N. T. and Bogomolo, L. M., Discharge of Tectonic Stress in the Earth Crust by High-power Electric Pulses for Earthquake hazard Mitigation, 2nd International Conference on Urban Disaster Reduction, 2007
- Zesta, E., Singer, H. J., Lummerzheim, D., Russell, C. T., Lyons, L. R., Brittnacher, M. J., In: Ohtani, S.-I., Fujii, R., Hesse, M., Lysak, R. L., The Effect of the January 10, 1997, Pressure Pulse on the Magnetosphere-Ionosphere Current Systems, *Geophysical Monograph Series*, volume 118, 2000
- Zhang Gui-Qing, Relationship between Global Seismicity and Solar Activities, *Acta Seismologica Sinica*, volume 11, pp. 495-500, 1998
- Zhou, X. and Tsurutani, B. T., Interplanetary shock triggering of nightside geomagnetic activity: Substorms, pseudo breakups, and quiescent events, *Journal of Geophysical Research*, volume 106, pp. 18957-18967, 2001