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Possible connection between solar activity and local seismicity

Emad M. H. Takla^{1*}  and Susan W. Samwel¹

Abstract

Recently, much attention has been paid to the relationship between solar and seismic activities toward earthquake (EQ) prediction. Some researchers believe in the existence of a connection between them; however, others completely refuse the existence of such a connection. In this study, the correlation between solar disturbances and occurrence of EQs during two consecutive solar cycles (SCs) 23 & 24 from 1996 to 2019 was investigated to explore such a relationship. The study was performed on both global and local scales. On a global scale, we studied the temporal variations of EQs number and the corresponding solar activity, represented by sunspot number. On the other hand, we selected several seismic zones characterized with high seismic activities and shallow depth EQs. For each zone we examined the day-to-day variations in the number of EQs and explored the space weather “chain of action” from the Sun to Earth in order to examine whether these events have an influence to increase the number of EQs or not. Results showed that, for the whole global seismicity, no clear correlation is found between EQs occurrence and solar activity, while for small active seismic zones, the connection between them is significant. An increase in the number of shallow EQs in the studied seismic zones is observed in association with the variations of examined space weather indices. Thus, the current study suggests a possible connection between solar activity and localized seismic activities. However, the solar-magnetosphere-lithosphere coupling and interaction during solar events need further study and investigation for a better understanding of their EQ triggering effects.

Keywords Solar activity, Seismic activity, Earthquakes occurrence, Geomagnetic storms, Space weather

1 Introduction

Space weather is defined as the variation occurring in the space environment that has the capability to impact the near-Earth environment. The primary driver of space weather is the Sun, which, despite the long distance to the Earth (150 million kilometers), can influence the Earth and its environment (Singh et al. 2021; Temmer 2021). The Sun is the main energy source for the whole solar system. It is a massive ball of electrically charged hot gas. The motion of these charged particles generates a powerful magnetic field that extends throughout our

solar system (Interplanetary Magnetic Field, IMF). The Sun is a dynamic body that continually emits radiation in the form of constant flow of charged particles known as solar wind. The eruptive processes, which arise on the solar surface, generate multitude of space weather phenomena. The explosive release of magnetic eruption from a sunspot area or a group through magnetic reconnection is called Solar Flare (SF) (Fletcher et al. 2011; Benz 2017). These eruptions are originated in the form of bursts of electromagnetic radiation, including X-rays and ultraviolet light. Ejections of large clouds of plasma eruptions from the solar corona associated with magnetic field are known as Coronal Mass Ejections (CMEs). These ejections propagate into the interplanetary (IP) space, where they are defined as Interplanetary Coronal Mass Ejection (ICMEs) (Chen 2011; Webb and Howard 2012). The elevated fluxes of nonthermal electrons, protons, and

*Correspondence:

Emad M. H. Takla
emad.takla@nriag.sci.eg

¹ National Research Institute of Astronomy and Geophysics (NRIAG),
Helwan 11421, Cairo, Egypt



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ions observed in situ are known as Solar Energetic Particles events. These events are originated from SFs and/or CMEs (Vlahos et al. 2019; Papaioannou et al. 2016; Trotter et al. 2015).

One of the most important space weather phenomena in the Sun–Earth connection is the Geomagnetic Storms (GSs), which are temporary disturbances in the Earth's magnetosphere. GSs are caused by either fast or massive CME or by the Corotating Interaction Regions (CIRs); which is produced when fast solar-wind streams, ejected from coronal holes, interact with slow streams (Lang 2009; Miteva 2020). The CME-driven storms are often stronger with relatively short duration, which is not the case for the CIR-storms that are weaker with comparatively prolonged duration. They usually occur during the early declining phase of a solar cycle (e.g., Chen et al. 2014; Grandin et al. 2019; Temmer 2021).

These space weather phenomena are known to cause negative consequences on the performance and reliability of the space-based and ground based technological systems (e.g., Samwel and Hady 2009; Samwel et al. 2019). The effects of geomagnetic disturbances on the activities of modern civilization have been recorded for over a century and reported in literature (e.g., Lanzerotti and Gregori 1986; Boteler et al. 1998). Recently, a debate on the impact of strong variations of space weather on the lithosphere and possible triggering of EQs is under way, which is the scope of the present study.

EQs are natural phenomena that can occur due to an abrupt energy release in the lithosphere that sometimes causes huge damage. Due to tectonic plate motions, stress accumulates in the lithosphere. When this stress is great enough, failure will take place and the lithosphere will break causing EQs (Bolt 1993; Takla et al. 2011, 2018). In addition to the plate motions as a main source of seismic activities, it is widely discussed that other external factors (outside the Earth) can trigger EQs. These factors are called “Earthquake triggers” (Tavares 2011; Takla et al. 2012). Solar and lunar eclipses, planetary alignment within the solar system, in addition to the space weather phenomena, are examples of external factors that can provoke EQs. Recently, the GSs generated due to the interactions and processes in the Sun–Earth system are introduced as an example of external EQ triggers. While several scientists support the idea that solar activity has an influence on seismicity by demonstrating some evidences and results of statistical analysis (Sobolev et al. 1998; Georgieva et al. 2002; Shestopalov and Kharin 2006; Belov et al. 2009; Gonzalez-Esparza et al. 2018; Novikov et al. 2020), some scientists totally refuse the assumption that solar activity can affect the global seismicity (Stothers 1990; Yesugey 2009; Love and Thomas 2013). Generally, EQs are caused by a combination of

factors. Sometimes one or two factors may dominate others, in this case the correlation is more visible; however, when many factors are involved, such correlation is barely seen. Therefore, drawing a conclusion whether there is or there is no correlation between seismic and solar activities from a single parameter is not reliable. So, it is very important to intensify research works concerning this controversial topic.

Even though several researchers have demonstrated a possible solar activity relationship with EQs, very few scientists have attempted to investigate the effect of space weather events such as SFs, CMEs, and GSs on the global seismicity. Thus, the present research investigates the possible correlation between space weather events and seismic activities through analyzing long-term data of both seismic and space weather indices. The vertical component of the Interplanetary Magnetic Field (IMF-Bz), flow pressure, and Disturbance storm time (Dst) index are the parameters used in the current study along with the solar events data such as Soft X-ray flare class, CME speed, particles fluxes, and CME angular width.

2 Data sources

In the present work, we started our study with examining the occurrence of EQs with magnitude 4+ on Richter scale from year 1996 to 2019 which are extracted from U.S. Geological Survey (USGS) website. Then we searched, within a time window of 4 or 5 days before all significant seismic activities, for the space weather events; including solar and interplanetary events, that may trigger such seismic activities.

For the long-term solar activity variation, we used the sunspot number, which quantifies the abundance of spots on the solar disk. As an index, sunspot number can be defined on a daily basis but because of the large day-to-day variation, it is usually averaged over longer periods. In our study, we used the yearly averaged values of sunspot number. The sunspot number index is extracted from the OMNIWeb Data Explorer—NASA.

For the short-term solar activity variations, we investigated different solar and interplanetary events to represent the space weather variations that may trigger such seismic activity, including SFs, Coronal Mass Ejections (CMEs) & its Interplanetary counterpart (ICME), solar energetic particles including protons (SEPs) & electrons (SEEs), GSs, in addition to the related variations in the Interplanetary magnetic field (IMF) and Solar Wind streams (SW). The soft X-ray peak flux (or flare class) which is defined as the flux in the soft-X ray band at the peak of the flare emission is used to represent the strength of the SFs. The onset and peak time, in addition to the flare class and helio-location are obtained from the GOES SXR flare listings. The time of the first occurrence

of the CME above the SOHO/LASCO C2 occulting disk, the projected on the plane of sky linear speed and the angular width are collected from the SOHO/LASCO CDAW CME catalog database (Yashiro et al. 2004). For the counterpart Interplanetary Coronal Mass Ejections (ICMEs), the information in terms of speed is obtained from Cane and Richardson ICME catalog (Richardson and Cane 2010; Cane and Richardson 2003). Concerning solar energetic particles, we benefit from the availability of online catalogs. For the case of the protons (SEPs), we used the proton flux detected by Wind/EPACT instrument, as reported in the Wind/EPACT proton event catalog (Miteva et al. 2018). Similarly for the electrons (SEEs), we adopted the results for the electron fluxes from the only available electron catalog to date (Samwel and Miteva 2021) based on the deflected electron data from ACE/EPAM instrument.

The disrupted solar activity conditions may lead to solar wind variations which in turn transfer energy from the solar wind into Earth's magnetosphere and cause Geomagnetic Storms (GSs). Earth's magnetosphere is a highly dynamic area around the Earth that responds dramatically to solar variations by producing changes in the radiation belts, changes in the ionosphere, and in the environmental electric currents (Zilli Vieira et al. 2019). The strength of IMF fluctuations is considered an important parameter affecting the geomagnetic field condition. The intensity of these disturbances can be expressed by variations in some solar wind parameters such as solar wind speed and flow pressure in addition to the orientation of the North–South component of Interplanetary Magnetic Field (IMF-Bz) which controls the amount of energy that can penetrate the magnetosphere (Dungey 1961). The severity of the Geomagnetic Storms (GSs) is expressed by the Disturbance storm time (Dst) index. It is a global geomagnetic activity index that is based on one-hour measurements from ground-based magnetometers at the dip equator. It measures the decrease in the

geomagnetic field due to the increase in the magnetospheric ring current. The large negative values of Dst index indicate the occurrence of intense GS (Sugiura 1991). The Dst index, with a time resolution of one hour, was obtained from the World Data Center at the University of Kyoto database. The north–south direction of the interplanetary magnetic field (IMF-Bz) in addition to the solar wind data with one hour time resolution were obtained from the OMNI website. Data resources are listed in Table 1.

3 Analysis and results

The analysis started with analyzing the seismic and space weather data to investigate the long-term trend of global seismicity during the last two solar cycles 23 & 24 and to find out the occurrence of any probable connection between them. The yearly number of EQs (shallow, intermediate, and deep EQs with $M \geq 4$) was calculated using a MATLAB script and compared with yearly average values of sunspot number and Dst index, which represent the solar activity and GS strength respectively, as shown in Fig. 1. Data analysis shows a slightly increasing trend of the global seismic activity during SCs 23 & 24 with a remarkable decrease in 2009 in addition to small fluctuations throughout the SC24. Thus, no clear correlation between the distribution of EQs and solar activity was found, which was demonstrated by the weak correlation coefficients (-0.35 and 0.28) between EQs no. with sunspot no. and Dst respectively as revealed in the right-side panel in Fig. 1. We believe that this weak correlation doesn't mean that there is no evident relationship between the EQs and solar activity variation. However, comparing all EQs of all magnitudes and depths all over the world with the solar activity variation might not be an appropriate way to investigate the actual relationship between solar and seismic activities. This is the same

Table 1 Summary of data resources used in the current study

Event	Website	Link/References
EQs	U.S. Geological Survey (USGS)	https://www.usgs.gov/natural-hazards/earthquake-hazards/research
SFs	GOES SXR flare listings	ftp://ftp.swpc.noaa.gov/pub/warehouse/
CMEs	CDAW LASCO CME catalogue	https://cdaw.gsfc.nasa.gov/CME_list/
ICMEs	Cane and Richardson ICME catalog	https://izw1.caltech.edu/ACE/ASC/DATA/level3/icmetable2.html
SEPs	Wind/EPACT proton catalog	http://newserver.stil.bas.bg/SEPcatalog/index.html
SEEs	ACE/EPAM electron catalog	https://www.nriag.sci.eg/ace_electron_catalog/
GSs	World Data Center, Kyoto University	http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html
IMF	OMNIWeb Data Explorer—NASA	https://omniweb.gsfc.nasa.gov/form/dx1.html
SW	OMNIWeb Data Explorer—NASA	https://omniweb.gsfc.nasa.gov/form/dx1.html

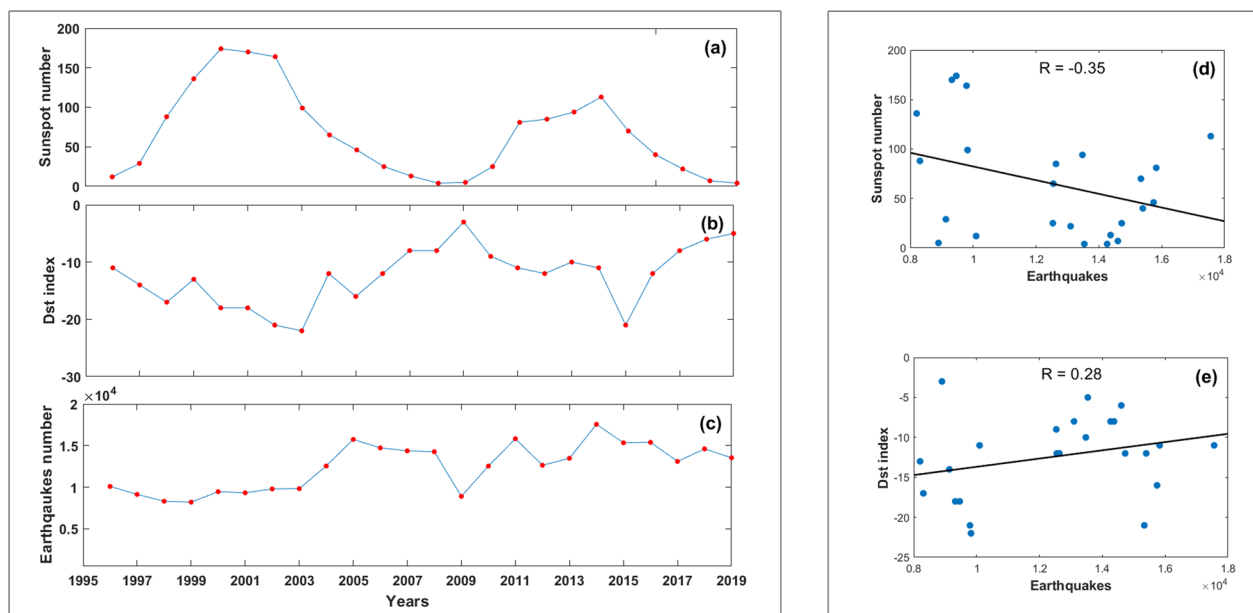


Fig. 1 Left side panel show the temporal variations during SCs 23&24 (1996–2019): **a** Yearly averaged values of sunspot number; **b** Yearly averaged values of Dst index; and **c** Yearly number of EQs. Right side panels represent correlation plots of EQs number against sunspot number (**d**) and Dst index (**e**)

strategy followed by the researchers who refuse the existence of such a relationship.

Since we were not able to find a clear link between solar and seismic activities, we decided to limit our study to shallow EQs (depth ≤ 70 km, according to e.g. Hedervari 1964; Al-Heety 2020). We examined day-to-day variations of EQs number by calculating the daily number of shallow EQs ($M=4+$) all over the world during 2004 (as a random example) and we compared them with the variation of the Dst index; flow pressure and IMF-Bz of the same year as shown in Fig. 2. These parameters reflect the disturbances generated due to the occurrence of space weather events. Three categories of correlation between the EQ's occurrence and variations in the space weather parameters are displayed in Fig. 2, illustrated by the blue, green and red rectangles. The first category (blue rectangle; Interval 1) represents the time interval that shows a high correlation between the increase in the seismic activity and the remarkable variations in the studied space weather parameters. The second category (green rectangle; Interval 2) indicates no remarkable increase in EQs number with observed clear variations in the studied parameters. The third category (red rectangle; Interval 3) presents the time interval with poor/no correlation between variation in the seismic activity and the examined parameters. Until this point, we still can't distinguish a clear link between solar and seismic activities. The absence of a remarkable increase in EQs number in the second category (Interval 2) may not be

a sign of poor correlation between the solar and seismic activities. However, an enhancement in EQs number may have occurred in some active seismic regions in association with strong solar events but this enhancement is still smaller than the global number of EQs (global background level of seismicity) at this time interval. As a result, we can't notice any clear increase in global EQs number. In addition, not all space weather phenomena can affect Earth and consequently increase seismic activities. It depends on a variety of factors, including strength of phenomena, in addition to relevance of the transport conditions in the interplanetary space. Thus, this increase in EQs number represented by the red rectangle (Interval 3) in Fig. 2 may have no relation with the solar activity and may have been caused by internal factors linked with tectonic activities as in case of the strong seismic activity occurred in Sumatra, Indonesia, 2004 (Stein and Okale 2005).

As we previously mentioned, causes of EQs can be classified as either internal (tectonic) such as folding, faulting, volcanic eruption or external (non-tectonic) related to the space weather disturbances. Generally, the external factors of EQs tend to influence shallow EQs (Sasorova and Levin 2007). In our opinion, the efficiency of space weather events (external factors) in triggering EQs can be overwhelmed by several factors such as the faulting type, the orientation of the fault plane, depth of EQ, the lithology and electric conductivity of the seismic zone. Thus, another way to investigate the correlation between

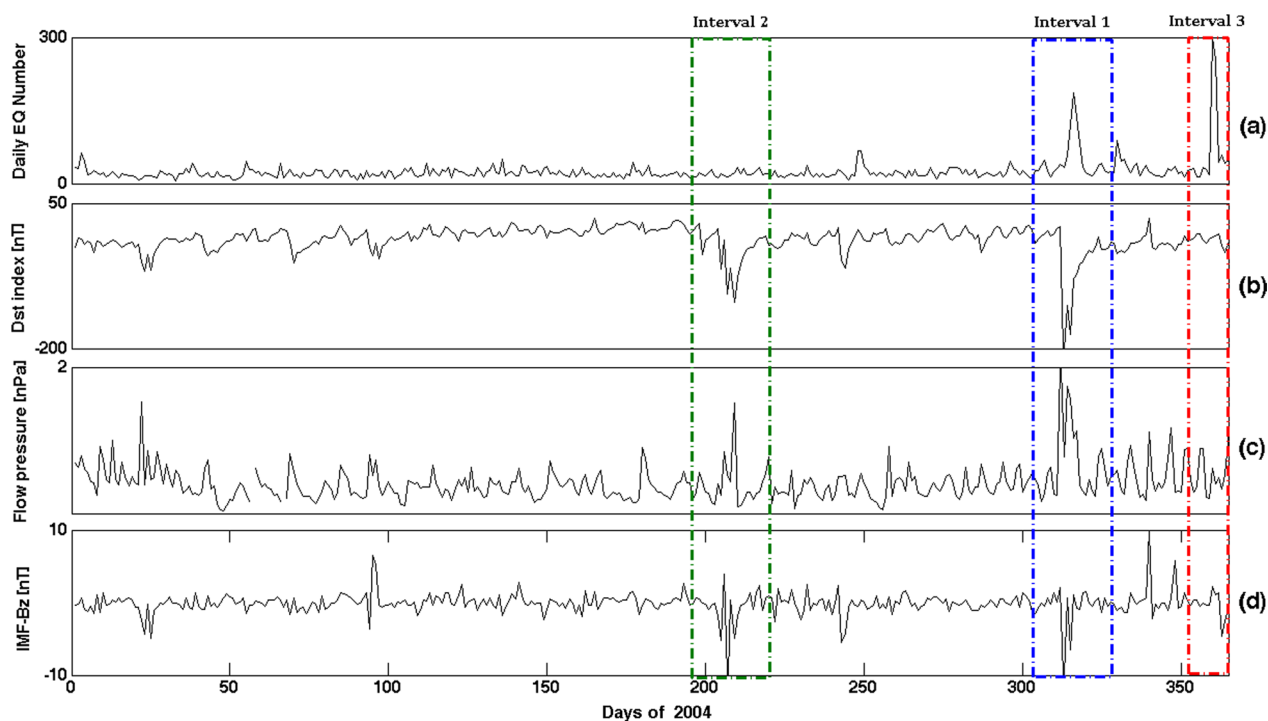


Fig. 2 Temporal variations in 2004: **a** Daily values of global EQs with $M=4+$; **b** Hourly values of Dst index; **c** Hourly values of flow pressure; **d** Hourly values of IMF-Bz

space weather events and seismic activities is to deal with shallow EQs events in small (local) active seismic zones to avoid, as much as possible, big changes in the factors controlling the occurrence of EQs. Therefore, to get a fair idea about the possible relationship between local seismic activities and the occurrence of space weather events, we selected six seismic zones (at different geographic locations all over the world) characterized with high seismic activities and shallow depth EQs. Figure 3 shows depth distributions of seismic activities that occurred at one of the selected seismic zones. It is clear from the upper panel that the hypocenters of seismic events occurred from 1996 until 2019 in this zone are mainly located at three shallow depths only, while the lower panel shows that the hypocenters of EQs are located at same depth (high possibility along one active fault) in this year (1998). In this case, we may have the same fault type, almost same orientation of the fault plane, nearly homogeneous underground lithology, and conductivity since we deal with small zone. Thus, eliminating the effects of these factors can help us to extract any possible relationship between solar and seismic activities.

For each seismic zone, we examined the day-to-day variations in the number of EQs to detect the time intervals showing high seismicity and try to find out their possible connection with the occurrence of space weather events. We calculated the daily EQs number (i.e., number

of earthquakes occurred in each day) at each zone and explored the chain of action from the Sun to Earth to find out whether these events lead to strong geo-effectiveness and preconditioning effects of high seismicity in each zone or not. Several cases of seismic activities that occurred at the selected seismic zones were examined for this purpose. The investigated seismic activities and the space weather events are demonstrated separately for each zone as follows: in Sects. 3.1–3.6.

3.1 Zone 1: South-East of Indonesia

Two seismic activities were examined at South-East of Indonesia with latitude range (N02-S10) and longitude range (E110-E130). The first seismic activity is represented in Figs. 4 and 5. The daily number of EQs, as calculated by a MATLAB script prepared for this aim, is shown in Fig. 4. While Fig. 5 is a seismicity map showing the distribution of EQs that occurred in this zone during the same time interval represented in Figure. An increase in seismic activity (as represented by the daily number of EQs in the upper panel of Fig. 4) was observed with a maximum peak occurred on November 9, 1998. So, we examined the space weather phenomena occurring prior to this seismic activity to detect any possible EQs provoking effect that may be related to these events. On November 4, 1998, halo CME was observed with speed of 523 km/s associated with C-class flare (C1.7) produced

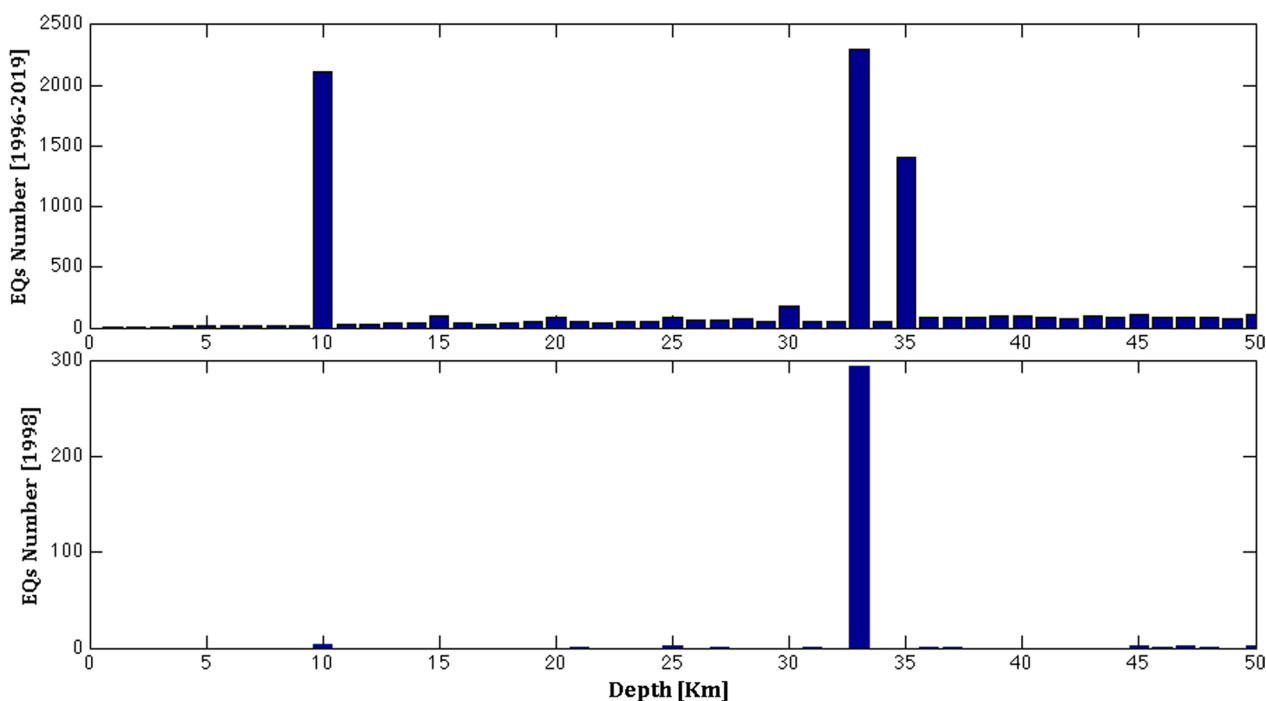


Fig. 3 Distribution of EQs occurrence at depth between 0 and 50 km in zone one that located at South-East of Indonesia from 1996 until 2019 in the upper panel and for one selected year (1998) in the lower panel

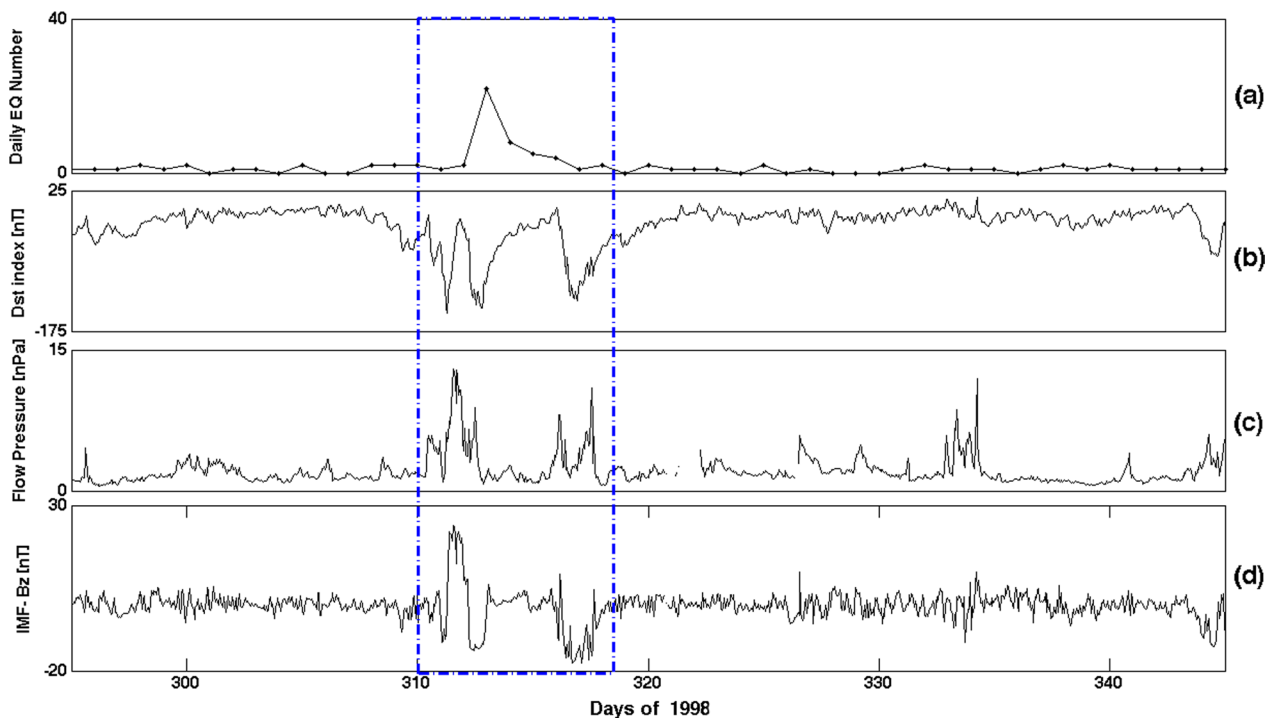


Fig. 4 Fifty-day temporal variations: **a** Daily values of shallow EQs with $M=4+$ occurred at zone one (first seismic activity); **b** Hourly values of Dst index; **c** Hourly values of flow pressure; **d** Hourly values of IMF-Bz. The blue vertical rectangle indicates the correlation between the increase of seismic activity and the variation of the selected solar parameters

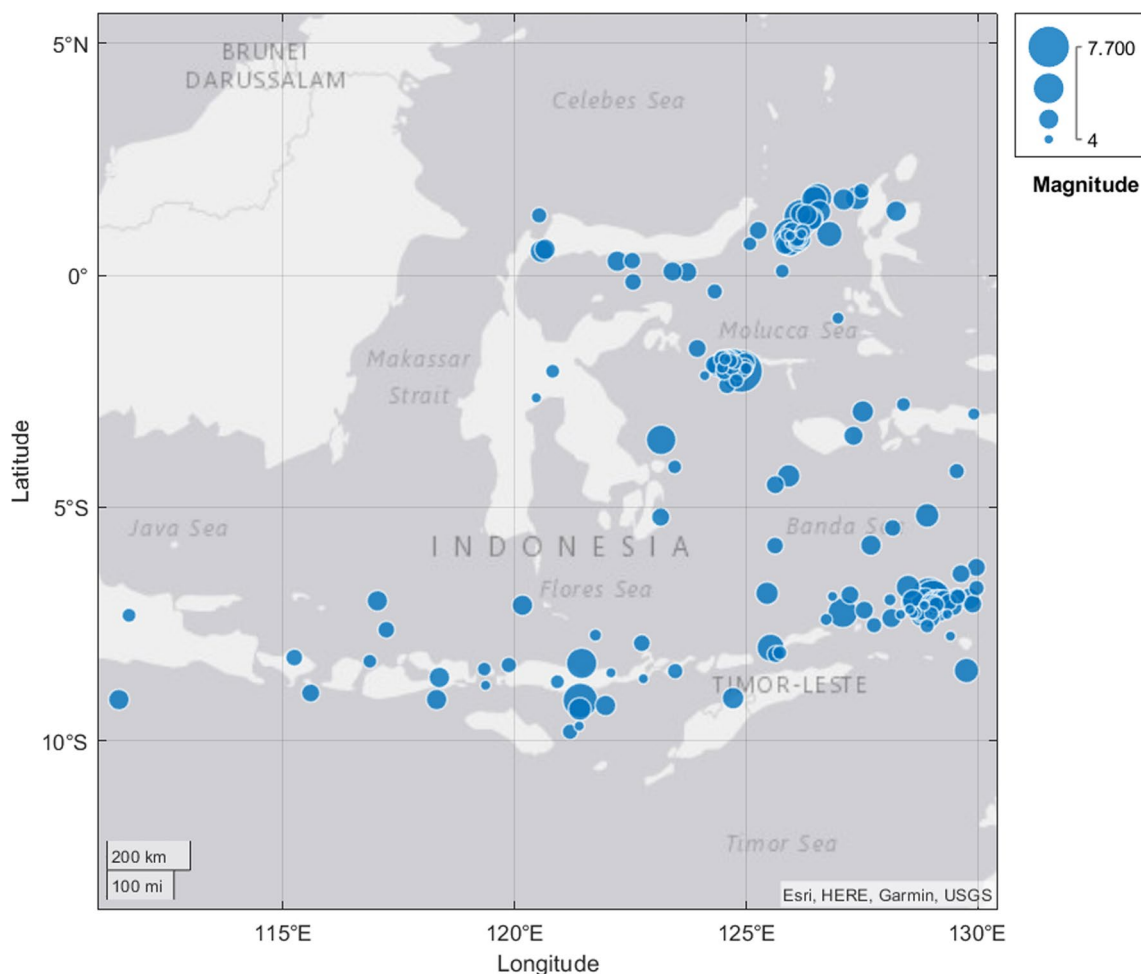


Fig. 5 Seismicity map shows the distribution of shallow EQs with $M=4+$ occurred at zone one (first seismic activity case)

on the North-West quadrant on the Sun from the active region 8375, followed by another halo CME with speed of 1118 km/s that is launched together with M-class flare (M8.4) on November 5. Consequently, two ICMEs arrived on November 7 at 07:00 UT and November 8, at 04:00 UT, respectively. Accordingly, the solar wind speed jumped to 535 km/s on November 7, and 593 km/s on November 8. In coincidence with that, the flow pressure showed a remarkable increase where it reached a maximum value of 13 nPa on November 8. Consequently, two GSs were detected on Earth on November 8 and 9 respectively in connection with these solar events. The Dst index drops to -149 nT and -142 , respectively. The IMF-Bz showed a clear and big change in both amplitude and direction from 24 nT in North direction to -14 nT in South direction during the observed GSs. For more information about these two events, refer to (Zhang et al. 2003).

The other seismic activity occurred between November 9 and 13, 2004 with a maximum peak of seismicity

on November 11, 2004, as represented in Fig. 6. Examining the occurrence of space weather events before the observed seismic activity showed that, in November 2004, an active region (AR) 10,696 was noticed on the east limb. During 3–6 November, eleven M-class flares were produced from this region as observed by GOES. Most of these flares were accompanied by halo high-speed CMEs observed by SOHO/LASCO. On November 7, a halo CME with speed of 1759 km/s was observed along with a strong X-class flare (X2.0). A SEP event was detected by WIND spacecraft on November 7, most probably linked to the X2.0 flare. During 9–10 November, the GOES X-ray sensor detected M-class (M8.9) and X-class (X2.5) flares, both were accompanied with halo high-speed CMEs with maximum speed of 3387 km/s. An enhancement in the daily proton flux was detected on November 10 that is likely linked to the X2.5 flare. The CMEs most probably interacted on their way to the Earth. Consequently, ICME was detected by ACE spacecraft on 7–8 November, comprising three shocks,

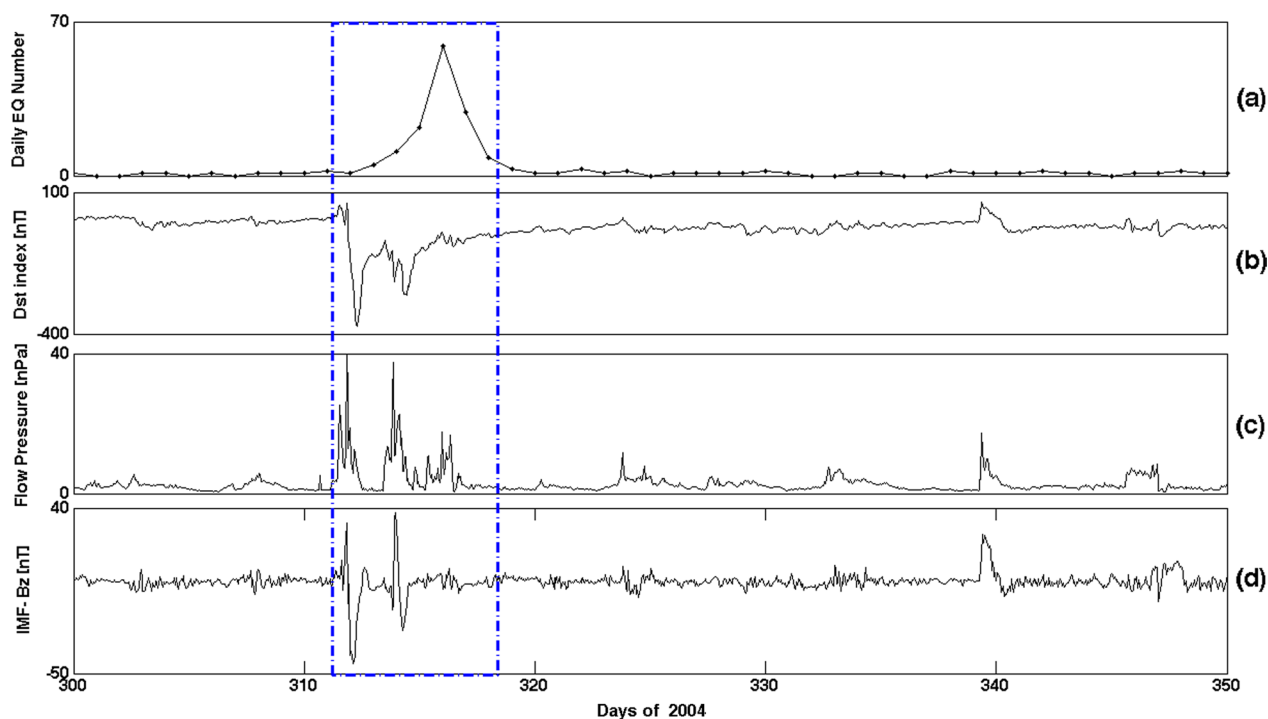


Fig. 6 Fifty-day temporal variations: **a** Daily values of shallow EQs with $M=4+$ occurred at zone one (second seismic activity); **b** Hourly values of Dst index; **c** Hourly values of flow pressure; **d** Hourly values of IMF-Bz. The blue vertical rectangle indication is the same as in Fig. 4

and a second ICME on 9–10 November, comprising two shocks. The solar wind speed reached 695 km/s on November 8 and 776 km/s on November 10. A significant increase in the flow pressure was recorded in connection with these solar events with maximum values reaching 40 nPa and 37 nPa on November 7 and 9 respectively. The interaction of the passing ICMEs with the Earth's magnetosphere produced complex variations in the Earth's geomagnetic field. The Dst index reached -373 nT due to the interaction of the first ICME during 7–8 November and -289 nT due to the interaction with the second ICME during 9–10 November. In association with these anomalous changes, the IMF experienced abrupt direction changes from 30 nT northward to -45 nT southward in association with the first ICME and from 38 nT northward to -27 nT southward with the second ICME. For more detailed information about this event, refer to (Trichtchenko et al. 2007).

3.2 Zone 2: Taiwan zone

An increase in the number of EQs was observed in Taiwan with latitude range (N20–N25) and longitude range (E119–E124). The seismic activity started on July 27, 2004, at this area and lasted for four days with maximum number of EQs occurred on July 28, 2004, as presented in Fig. 7. The space weather data indicated that, on July 22, 2004, the active region 10,652 produced three M-class

flares with the largest of M9.1 class at 00:32 UT from the north-east quadrant of the Sun. A CME was observed soon after the M9.1 flare although it was not earthward directed. Solar wind speed at ACE steadily increased after the impulse from 376 km/s to 702 km/s while Dst fell to -85 nT. On July 23, 2004, M-class flare (M1.7), produced from the same active region 10,652, that was linked with halo CME with speed (824 km/s), producing solar energetic electron event. A minor shock was observed at ACE on July 24, at approximately 06:00 UT. In addition, on July 25, the same active region produced 4 M-class flares with the largest of M7.1 class. A long with M1.1 flare peaked at 15:14 UT, a halo CME with speed of 1333 km/s was detected heading to Earth. These eruptions were associated with strong particles events, both proton and electron populations. A shock was recorded by ACE on July 26 at 22:27 UT by ACE, the solar wind speed was elevated in the 550 to 700 km/s range. A severe GS was observed, likely linked to the complex series of CMEs observed on 22 and 23 July. On July 27, a GS is detected following the transit of the halo CME conjointly with the long duration M1.1 flare on 25 July 25. Solar wind speed increased from the already elevated levels near 600 km/s to over 1072 km/s and the flow pressure jumped to 25 nPa. The Dst index reached its minimum value (-170 nT) on July 27. In correlation with these space weather events, clear changes in the IMF-Bz were observed where

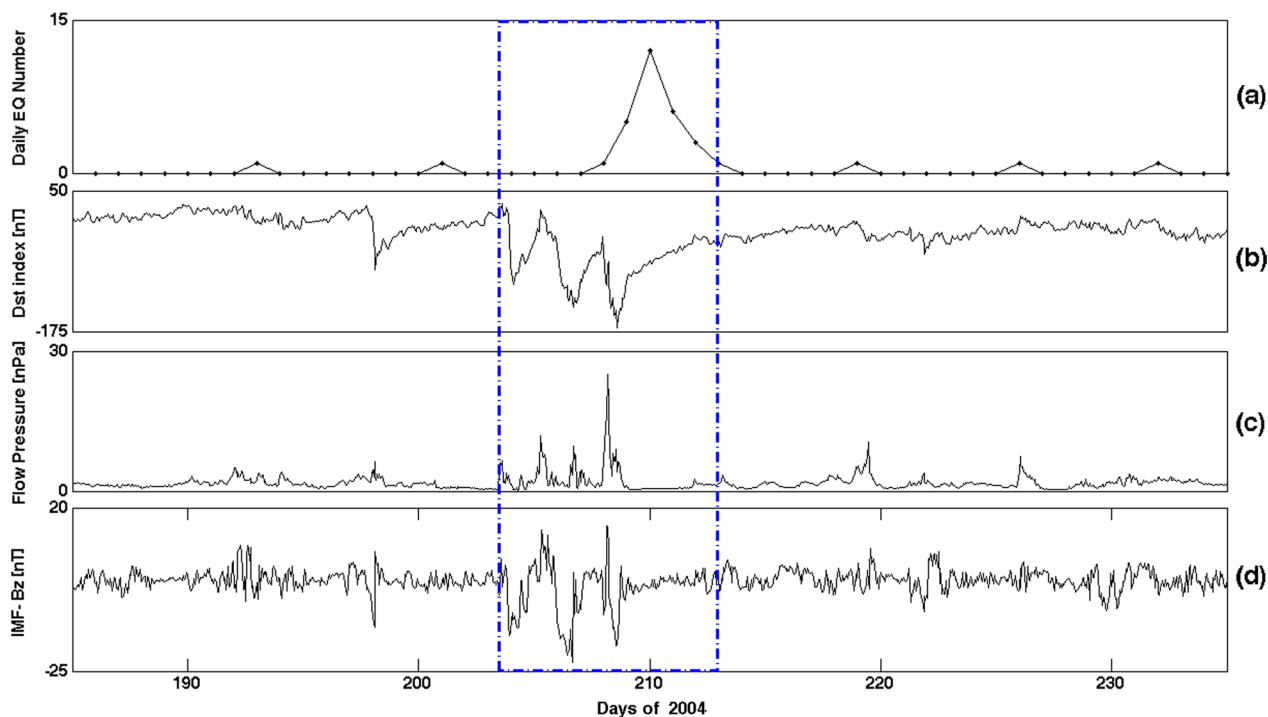


Fig. 7 Fifty-day temporal variations: **a** Daily values of shallow EQs with $M=4+$ occurred at zone two; **b** Hourly values of Dst index; **c** Hourly values of flow pressure; **d** Hourly values of IMF-Bz. The blue vertical rectangle indication is the same as in Fig. 4

the IMF-Bz changed its direction several times with magnitude ranging between -22nT and 15nT .

3.3 Zone 3: East of Japan zone

On August 27, 2018, a seismic activity was detected at east of Japan, with latitude and longitude ranges N35-N40 and E140-E142 respectively, as revealed from the day-to-day variation in the EQs number as shown in Fig. 8. Concerning the space weather phenomena, strong GS was seen on August 25–26, 2018, with weak solar flare activity. It was shown that, a strong GS (Dst index = -171nT) occurred on August 26, 2018, despite the very weakened disturbances on the Sun and the low solar wind speed. As reported by (Piersanti et al. 2020), a slow CME with angular width of 45 degree, hardly visible by SOHO/LASCO, was recorded on August 20, 2018, at 16:00 UT. A filament eruption observed on August 20 is presumed to be the most probable source of this CME. At the time of the CME lift-off the Sun, a sizable coronal hole was present that would generate a fast solar wind stream that could affect the CME propagation. Thereafter an ICME was recorded by WIND spacecraft, observed at Earth's orbit between 25 and 26 August leading to a jump in the solar wind speed from $\sim 370\text{ km/s}$ to $\sim 550\text{ km/s}$ on August 26 and the flow pressure value reached 6 nPa , resulted in a GS with Dst index falls to -174 nT . In addition, the

IMF-Bz showed a southward sudden change in coincidence with these variations with minimum value $\sim -15\text{ nT}$ on that day.

3.4 Zone 4: South of Alaska zone

Figure 9 represents the investigated seismic activity recorded at south of Alaska with latitude range N55-N65 and longitude range W125-W170. A local seismic activity started on May 4, 1998, and lasted for four days with maximum value on May 6, 1998. By Examining the space weather data, we found that, on May 1, 1998, a halo CME at (22:36 UT) associated with M-class flare (M1.2) produced from A8214 was detected, followed by another halo CME with speed of 938 km/s , along with much stronger X-class flare (X1.1) in the south-west quadrant of the Sun on the next day, May 2, followed by SEP event produced by the X-class flare, as observed by WIND Spacecraft. As a result, solar wind speed, as registered by ACE, jumped to 829 km/s with clear variation in the flow pressure with maximum value about 37 nPa causing large GS detected at Earth on May 4, 1998, as represented by Dst index which fall to -205 nT . In addition, the IMF was directed southward and reached its minimum value during the storm time ($Bz < -20\text{ nT}$).

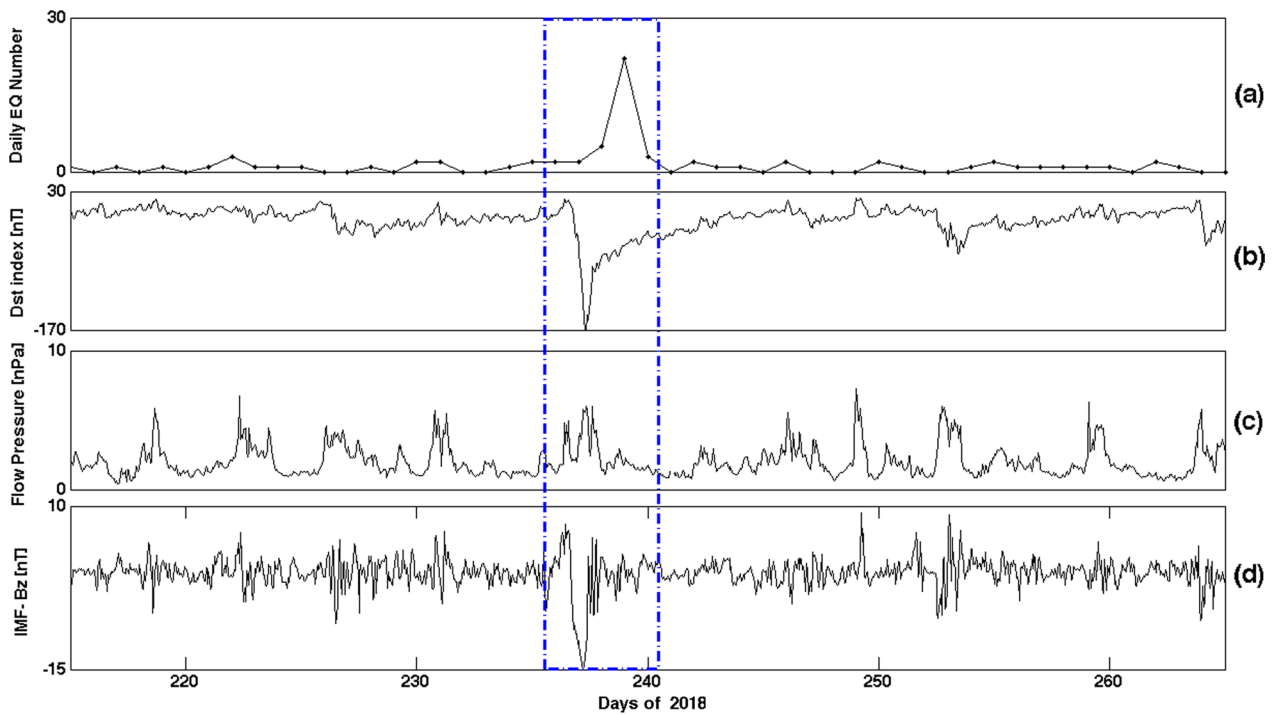


Fig. 8 Fifty-day temporal variations: **a** Daily values of shallow EQs with $M=4+$ occurred at zone three; **b** Hourly values of Dst index; **c** Hourly values of flow pressure; **d** Hourly values of IMF-Bz. The blue vertical rectangle indication is the same as in Fig. 4

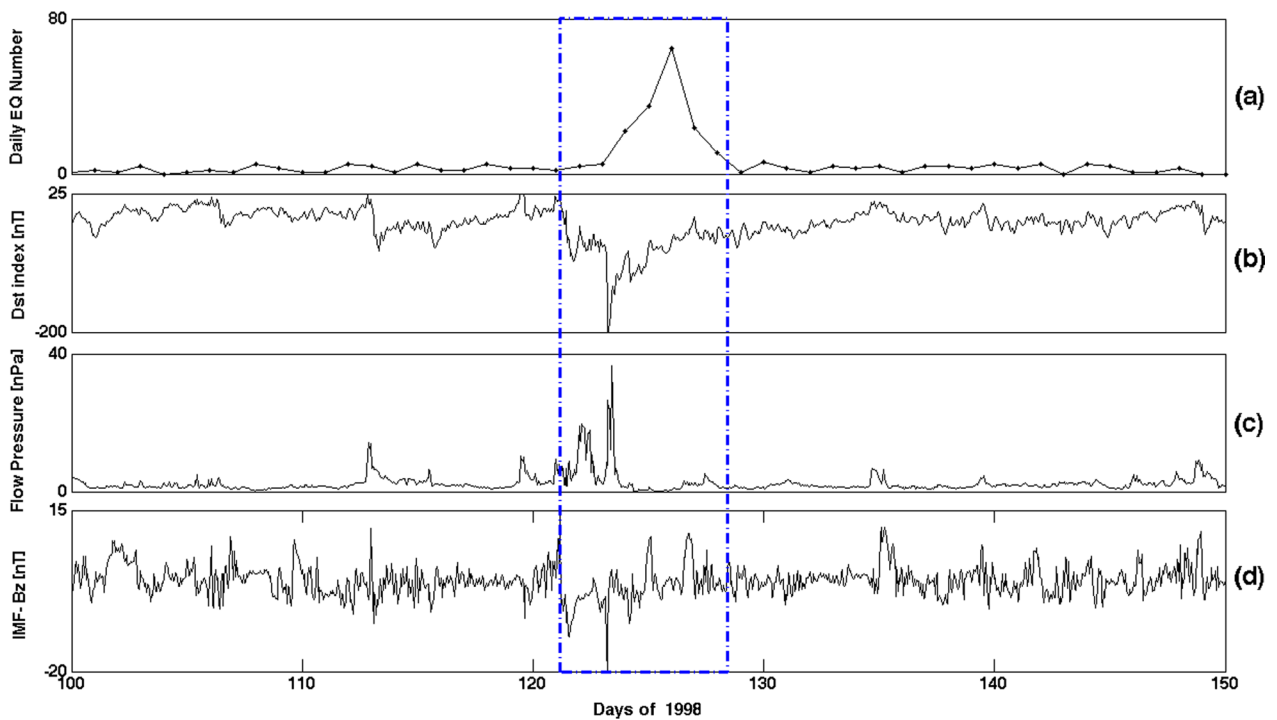


Fig. 9 Fifty-day temporal variations: **a** Daily values of shallow EQs with $M=4+$ occurred at zone four; **b** Hourly values of Dst index; **c** Hourly values of flow pressure; **d** Hourly values of IMF-Bz. The blue vertical rectangle indication is the same as in Fig. 4

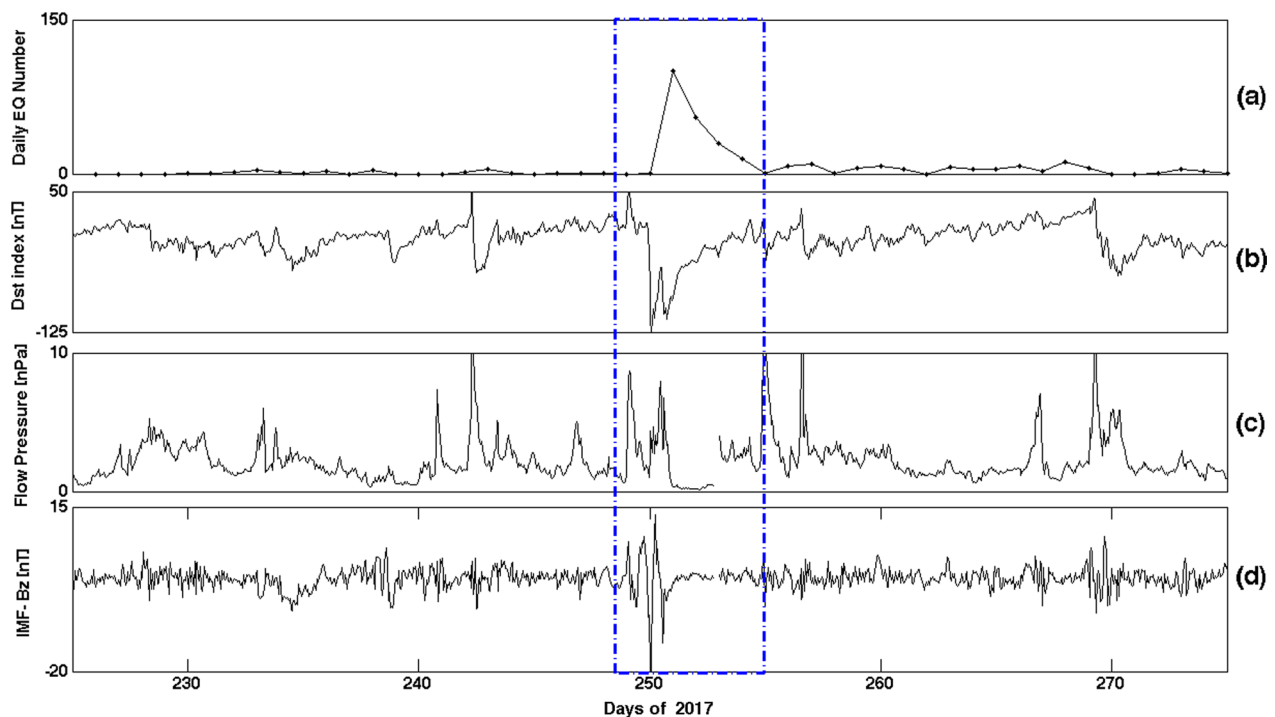


Fig. 10 Fifty-day temporal variations: **a** Daily values of shallow EQs with $M=4+$ occurred at zone five; **b** Hourly values of Dst index; **c** Hourly values of flow pressure; **d** Hourly values of IMF-Bz. The blue vertical rectangle indication is the same as in Fig. 4

3.5 Zone 5: West of Mexico zone

On September 8, 2017, sudden increase in the number of EQ events observed at West of Mexico at latitude range N10-N30 and longitude range W60-W110. It started to decrease gradually and recovered after a few days as we can see in Fig. 10. The interval from 4 to 8 September was one of the most flare productive periods of the solar cycle 24. The solar active region AR12673 produced more than a dozen of M-class flares and two X-class flares; X2.2, X9.3 flares as observed by GOES 16. On September 4, An M5.5 flare was produced, along with halo CME with speed of 1418 km/s, followed by a halo CME with speed of 1571 km/s, associated with X9.3 flare on September 6 as registered by SOHO/LASCO. Enhancements in the proton and electron fluxes were detected by WIND and ACE spacecraft over September 6, 7 2017. These events were related to the halo CME that occurred on September 6, 2017 (12:24 UT). The early arrival of the coronal mass ejection (on September 7 and 8) produced severe GS peaked on 8 September represented by the Dst index, which fell to -124 nT. The flow pressure value was about 9 nPa on that day. Moreover, a clear change in the IMF-Bz direction was detected on that day from -21 nT to 14 nT.

3.6 Zone 6: West of Chile zone

Examination of the daily values of EQ events indicated the occurrence of a seismic activity at west of Chile at latitude range S25-S35 and longitude range W66-W77. The activity started on May 31, 2003, as shown in Fig. 11. Regarding the occurrence of space weather events, a solar wind shock was observed at 1:52 UT by ACE on May 29. The source of this disturbance was likely a halo CME with speed 509 km/s as observed by SOHO/LASCO at 06:50UT. This CME was likely associated with M-class flare (M1.6) observed by GOES at 06:26 UT. Another strong shock was observed at 18:30 UT by ACE on May 29. This shock was caused by the arrival of 2 halo CMEs, which were observed after X1.3 flare on May 27 and X3.6 flare on May 28. Soon after the arrival of this disturbance, a severe GS was detected on Earth late on May 29, with Dst index reached -144 nT. The solar wind speed jumped from 465 km/s to 793 km/s. On the same day, a quick increase in the flow pressure was recorded with a maximum value of 70 nPa. A change in the IMF-Bz direction occurred southward with magnitude value -16 nT then followed by a sudden change to 24 nT Northward direction.

Finally, it is worth mentioning that all the studied cases showed a clear correlation between the increase in the EQs number and the remarkable variations in the examined parameters as shown by blue rectangles in Figs. 4, 5,

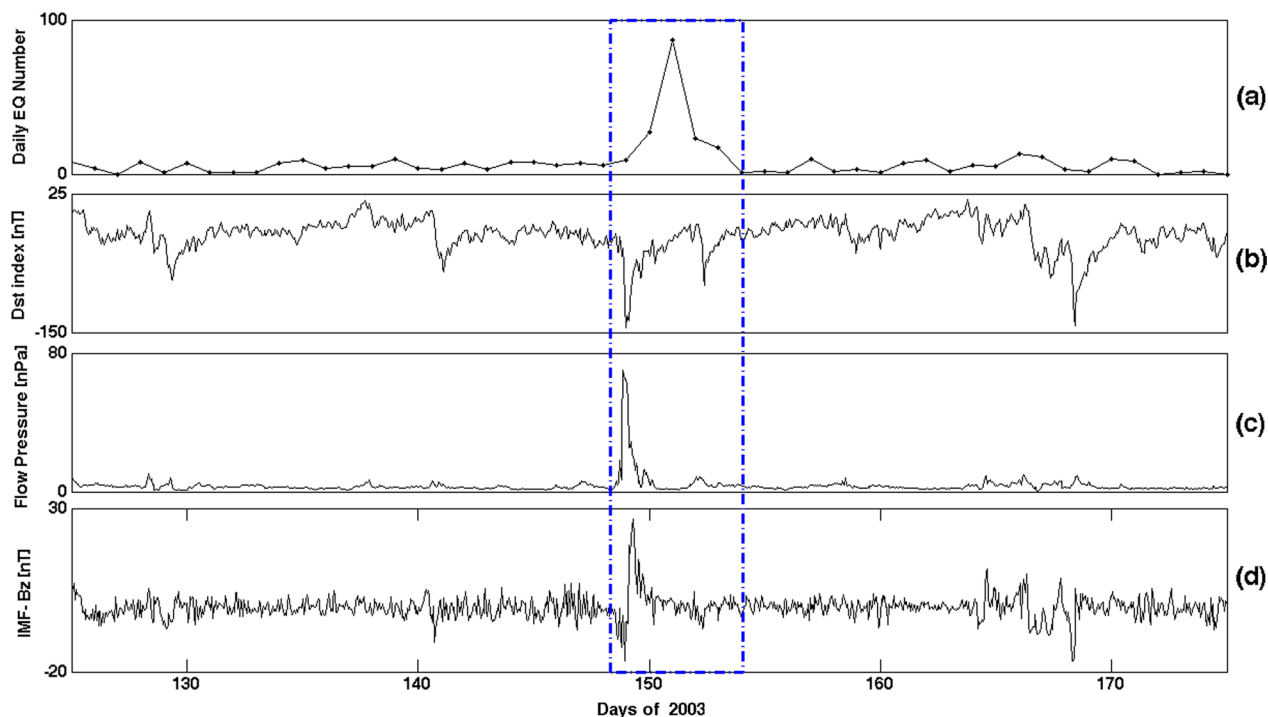


Fig. 11 Fifty-day temporal variations: **a** Daily values of shallow EQs with $M=4+$ occurred at zone six; **b** Hourly values of Dst index; **c** Hourly values of flow pressure; **d** Hourly values of IMF-Bz. The blue vertical rectangle indication is the same as in Fig. 4

6, 7, 8, 9, 10, 11. After examining the occurrence of space weather events to find out their possible connection with the observed increase in the seismic activity at each studied zone, we found that the majority of the peaks of seismic activities at all studied zones are preceded by the occurrence of strong SFs, of X and M classes, and halo CMEs with high speed ($\sim >900$ km/s) which indicates a possible connection between them. The increase in the EQs number took place about 1–3 days after the occurrence of the GSs linked with the examined solar events. An important observation is that the magnitude and direction of IMF-Bz along with the solar wind speed are significant factors in relating the increase of the seismic events to the GSs. During the examined seismic activities, the IMF-Bz had big changes in magnitude and direction (mostly to southward direction) and the solar wind characterizing with high speed. This observation needs further investigations to understand the role of IMF-Bz in such observation.

4 Discussion

The overview of studies completed to-date on a relation of the Earth's seismicity and solar activity indicate blurred and contradictory results. While there are studies against the assumption that the solar activity can provoke the seismic activity, other studies support the hypothesis on electromagnetic triggering of EQs, when

severe space weather generates geomagnetically-induced underground currents in the conductive faults matured for dynamic failure (Sobolev et al. 1998; Han et al. 2004; Hagen and Azevedo 2017; Gonzalez-Esparza et al. 2018; Sorokin et al. 2019, 2023; Novikov et al. 2020, 2020; Zeigarnik et al. 2022).

Our study comes in line with supporting the idea of a possible relationship between solar and seismic activities. The obtained results suggest a possible link between the occurrence of space weather events and seismic activity. The observed association between the geomagnetic disturbances due to solar storms and the occurrence of EQs in the current work provides clear evidence on the influence of strong space weather events on the EQs occurrence as shown in Figs. 4, 5, 6, 7, 8, 9, 10, 11.

The question arises here whether the occurrence of strong space weather events can really trigger EQs or not. If the Earth happen to be in the path of the flare or CME, it takes 8 min for flares to reach Earth, while for CME, it takes 1–4 days to propagate from the Sun to Earth depending on its speed which ranges from slower than 250 km/s to as fast as 3000 km/s. When SF and CMEs emitted by the Sun reach the Earth, they cause changes in the ionosphere conductivity, which in turn generate temporary sudden electric and geomagnetic field perturbations (Sorokin et al. 2019). These geomagnetic disturbances are known as GSs. If the GSs are driven by CMEs,

as in the cases understudy in the present work, they may have greater effect on Earth than the CIR-driven storms which are known to have a greater effect on the space-based systems (Borovsky and Denton 2006). Sometimes the Sun emits CMEs at a time when the magnetic-field lines of the Earth and Sun are directly connected. When these events occur, we can experience a truly large magnetic storm. Another cause of the GSs is the direct link that sometimes occurs between the Sun's magnetic field and the Earth's magnetic field. When such a connection takes place, charged particles, traveling along magnetic-field lines, can easily enter the magnetosphere and generate currents that cause temporary geomagnetic field variations. These geomagnetic disturbances induce powerful currents in the Earth's crust and upper mantle. Sobolev et al., (2001) and Zakrzhevskaya and Sobolev (2002) examined the probable influence of the GSs on seismicity at region of Kazakhstan and Kyrgyzstan. They concluded that there is a correlation between GSs and the seismic activity at studied region with a maximum effect between 2 and 7 days after the sudden commencement.

Another important question is whether the induced lithospheric currents related to geomagnetic disturbances can provide enough energy for EQ triggering or not. It is known that the Sun-Earth system is a complicated open dynamic system with various complex processes. The seismicity of the Earth can be a part of this Sun-Earth system. The relationship between seismicity and the chain-of-action from the Sun to Earth has been considered ambiguous until now. More than forty years ago, field experiments using direct electric current pulses injection were carried out at two different geophysical test sites. However, the main goal of these experiments was to monitor the electromagnetic precursors associated with strong EQs, the results of monitoring the seismic activity in the vicinity of the test sites indicate a change in the seismic activity in connection with these experiments. Tarasov et al. (1999) reported a possible triggering effect of impulsive electrical signals on seismic activities. By analyzing variations of the number of EQs in association with the electrical impulse signals, they inferred that the number of EQs tends to increase 3–4 days after the electrical signal passage. The duration of this activation stage is a few days, and the dimensions of the possibly affected area are on the order of a few hundred kilometers. Numerical estimation indicates that the density of induced lithospheric currents by geomagnetic disturbances generated in association with solar storms at EQ hypocenter (10^{-6} A/m²) is almost similar to the current density generated by artificial power sources (10^{-7} – 10^{-8} A/m²) that caused an increase in the seismic activity at the two test sites (Tarasov et al 1999). These field results were verified under laboratory conditions

(Novikov et al. 2017; Zeigarnik et al. 2022). Based on results of these field and laboratory experiments, we can assume that similar EQ triggering phenomena may occur due to the interaction between the induced electromagnetic currents (connected with the occurrence of SFs and CMEs) and lithosphere of active seismic zones.

The most controversial issue in this research field is the physical mechanism that can investigate the connection between the occurrences of space weather events and seismic activities. Different physical mechanisms are proposed to explain such a connection. The first one is that the generated electric currents transferred to the lithosphere can be converted into mechanical energy via inverse piezoelectric and electrokinetic effects, which increase the mechanical stresses in the lithosphere. Duma and Ruzhin (2003) have introduced the physical mechanism to relate solar activity and EQ events by introducing the possible influence of Lorentz force (torque) into the lithosphere, which may play a role in triggering EQs. Another suggested triggering effect is that; GSs would result in anomalies of geomagnetic field and in eddy currents in the fault planes. These eddy currents heat the rocks in the fault zones and therefore decrease the shear resistance and the static friction limit of the stressed rock, which in turn triggers the occurrence of seismic events (Sobolev et al. 1998; Zolotov et al. 2010).

Finally, we would like to emphasize an important issue, which is that, not all solar activity and subsequent geomagnetic disturbance trigger EQs since there are several factors included in their relationship as we mentioned before and discussed in detail in the literature (e.g. Sorokin et al 2023). Among these factors, the sensitivity of the EQ faults to the induced electromagnetic currents, the electric conductivity of the seismic zone, fault orientation with respect to the direction of geomagnetically induced underground currents, and the amount of stress accumulates at the fault zone. In addition, the severe the solar events, the higher the geomagnetic disturbances and higher induced currents in the earth's crust that can significantly increase the force on the lithosphere which may affect the state of metastable faults and could possibly trigger the seismic activity.

5 Conclusion

Even though various studies have reported a relationship between solar and seismic activities, discussions and arguments are still arising concerning their connection. The aim of the present study is to investigate the possible influence of space weather phenomena on EQs occurrence. The study is based on worldwide EQs events during about 25 years (1996–2019) along with both geomagnetic indices and solar parameters during the same period. The results of the current study indicate a good

correlation between the examined geomagnetic indices, solar parameters, and the seismic activities when we dealt with small active seismic zones.

In conclusion, we can say that the occurrence of solar events as SF and CMEs causes turbulence in the ionosphere and magnetosphere leading to produce geomagnetic disturbances which in turn generate underground currents that play an important role in triggering the seismic activity by accelerating the release of stress stored in the crustal rocks. In this case, we can observe a good correlation between GSs and seismicity as the number of EQs tends to increase directly after solar events and geomagnetic disturbances. Therefore, geomagnetic disturbances can be a key parameter in triggering some seismic events.

Finally, however, still there are debates and ambiguities concerning the connection between solar activity and EQs occurrence, the current results in somehow support the presence of such connection, especially with shallow depths EQs at small seismic regions. The present study introduces only preliminary results that wait for more investigations. Thus, exploring the possible connection between solar and seismic activity for larger number of cases are worth performed in the future. In addition, we plan to study the impact of the solar and interplanetary variations on the global seismicity, statistically, and investigate the controlling factors which dominate the solar-seismic relationship as a follow up study.

Abbreviations

EQ	Earthquake
GS	Geomagnetic storm
IMF	Interplanetary magnetic field
CMEs	Coronal mass ejections
IP	Interplanetary
ICMEs	Interplanetary coronal mass ejection
SEPs	Solar energetic particles events
CIRs	Co-rotating interaction regions
IMF-Bz	The North–South component of the Interplanetary Magnetic Field
Dst	Disturbance storm time
AW	Angular width
SC	Solar cycle
SW	Solar wind

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Author contributions

EMT: Conceptualization, Investigation, Methodology, Validation, Data curation, Formal analysis, Software, Visualization, Writing—original draft,

Writing—review & editing. SWS: Investigation, Validation, Data curation, and writing original draft, Writing—review & editing. Both authors read and approved the final manuscript.

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