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A comprehensive study of geomagnetic and TEC disturbances in relation to M $\geqslant$ 5.0 earthquakes

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Abstract

Previous studies have demonstrated the interaction between multiple layers of the Earth and seismic activity, specifically the lithosphere - atmosphere – ionosphere (LAI) coupling, which is the focus of the present study. Anomalies in LAI parameters, such as variations in geomagnetic field and total electron content (TEC) before seismic activity, have been regarded as earthquake precursors by previous researchers. However, earlier studies used only single parameters and had a limited number of case studies. This study aimed to investigate pre-earthquake anomalies using a dual-parameter approach. Geomagnetic field and TEC variations were used to investigate the relationship between the Earth's layers and earthquakes. Utilising global geomagnetic data and TEC data, a comprehensive analysis was conducted on the variations of geomagnetic and TEC data for the 60 days preceding and five (5) days following the occurrences of the 694 earthquakes with magnitudes greater than and equal to 5.0 (M $\geqslant$ 5.0) in the Japan region in 2011. Following the exclusion of days with geomagnetic storms, referred to as disturbed days, this investigation focused solely on undisturbed days. This study explored and compared geomagnetic and ionospheric disturbances during these undisturbed days preceding the earthquakes. Both geomagnetic and TEC precursors were significantly found in moderate and shallow earthquakes. It was revealed that, preceding the studied earthquake events, anomalous behaviours were evident in both geomagnetic and TEC variations, and these behaviours persisted even on undisturbed days. The study also observed that anomalous TEC parameters occurred within the same time frame as the geomagnetic anomalies, and they were found to be detected a month before the earthquakes. The occurrence rate of the geomagnetic precursors was higher of 65 %, than that of the TEC precursors of 11 %. These observations suggest that the preparation process for earthquakes could impact the ground and upper atmosphere, as described by the LAI coupling mechanism.

Keywords: Geomagnetic diurnal variations; Earthquake precursor; SuperMAG database; Diurnal variation ratio (DVR); Total electron content (TEC)

1. Introduction

Earthquakes are major natural hazards that can cause considerable damage and loss of life. This has prompted numerous studies to explore the potential of earthquake precursor studies. These studies attempt to identify and

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relate anomalies occurring in different layers of the Earth, which could provide early warnings and mitigate the impact of these devastating events. The lithosphere-atmosphere–ionosphere (LAI) coupling has been extensively studied in recent years owing to its potential influence from seismic activity. Several hypotheses have been proposed regarding the mechanism of LAI coupling, as seen in studies like Pulinets and Boyarchuk (2004) and Hayakawa et al. (2021). These include changes in atmospheric conductivity and the generation of electric fields in seismoactive regions, where such changes are believed to lead to perturbations in geomagnetic variations and ionospheric total electron content (TEC). The generation of electrical charges (electrification) due to microfractures in the subsurface caused by earthquakes enables the detection of pre-seismic anomalies in geomagnetic and TEC variations. These coupling mechanisms explain the emergence of ionospheric TEC disturbances and geomagnetic field variations within 30 days leading up to earthquake events, as reported in previous studies (Hasbi et al., 2011; Hayakawa et al., 2021; Zulhamidi et al., 2023b). Given that geomagnetic and ionospheric disturbances can be affected by numerous sources other than earthquakes, such as solar activity, discerning between precursory seismic signals and other effects poses a challenge (Fagundes et al., 2024; Wu et al., 2025).

Numerous studies have shown a significant relationship between these LAI parameters, particularly geomagnetic and TEC variations, and earthquakes (Hasbi et al., 2011; Hayakawa, 2015; Zulhamidi et al., 2023b). This study focused solely on these two parameters as they are part of a well-established monitoring system and are among the most frequently observed and studied earthquake precursors. While the Global Positioning System (GPS) based TEC measurements provide high spatial and temporal resolution, the ground-based magnetometers offer continuous and long-term monitoring capabilities, making them among some of the most reliable tools for pre-seismic disturbances monitoring. Several studies have consistently identified disturbances in geomagnetic and TEC variations days to hours before significant seismic events (Naaman et al., 2001; Pulinets and Boyarchuk, 2004; Pulinets et al., 2007). These disturbances, detected in the daily variations of these parameters, have been identified as precursors to earthquake occurrences. Increases in occurrences of geomagnetic disturbances have been observed at least a month before significant seismic events, as identified by Yusof et al. (2021) and Zulhamidi et al. (2023a) in their study. Meanwhile, TEC changes have shown anomalies occurring from days to weeks prior to seismic events, as reported by Sasmal et al. (2021) and Dong et al. (2022). Understanding the relationship between LAI coupling and seismic activity is crucial for predicting and mitigating the effects of earthquakes. To enhance earthquake monitoring study, study using different types of parameters that represent different layers of the Earth, through both ground- and satellite-based observational data, are essential.

Each of the past studies has shown different time ranges for geomagnetic and TEC anomalies, spanning from six (6) hours to 36 days before the earthquake occurrences (Zulhamidi et al., 2023b). However, only a few studies have reported the effects of earthquakes on geomagnetic variations. For instance, Yusof et al. (2021) concluded from a statistical analysis that anomalies can be detected from one (1) to three (3) weeks prior to earthquake occurrences when normal variations have ceased. Similarly, Hayakawa et al. (2021) found that the electromagnetic anomalies studied in their research were concentrated a week to nine (9) days before the earthquake day. Many studies have been conducted to monitor the effect of seismic activity on TEC variations. Hasbi et al. (2011) detected TEC anomalies within a few hours to six (6) days prior to some of the major earthquakes in Sumatra from 2004 to 2007. Correspondingly, Tao et al. (2022) also reported significant TEC anomalies about a week before the 2007 M7.5 Jakarta-Java earthquake, directly over the epicentre. To further examine the consistency of these anomalies, Akpan et al. (2024) analysed the Vanuatu and Honshu earthquakes and detected the earliest anomalies 20 days prior to the earthquakes. Additionally, several past studies have documented ionospheric response following the effects of earthquakes. For example, Yaso et al. (2013) recorded co-seismic oscillations seven (7) to 14 min after the great 2011 M9.0 Tohoku earthquake. Similarly, Tsugawa et al. (2011), who conducted a study on the ionosphere's response to the same earthquake, observed disturbances that appeared as sudden depletions seven (7) minutes after the event, near the epicentre.

Although many studies have discussed the effects of earthquakes on geomagnetic and TEC variations, there has been little discussion on the simultaneous relationship between these two parameters. Naaman et al. (2001) critically highlighted the scarcity of such comprehensive studies. Likewise, Zulhamidi et al. (2023b) in their review discussed the challenges and limited number of studies that simultaneously analyse multiple ionospheric parameters, including geomagnetic and TEC anomalies, in the context of earthquake precursors. Understanding this relationship is important as it shows the interactions of LAI coupling with seismic activity and its potential as an earthquake precursor. One of the challenges is distinguishing between the ionospheric anomalies caused by seismic activity and those resulting from other sources. This paper seeks to contribute to the ongoing debate on the reliability and accuracy of earthquake precursors by investigating the responses of two different parameters, namely the geomagnetic field and ionospheric total electron content variations, prior to earthquakes. Specifically, we propose that the precursor signals can be observed in both geomagnetic and TEC variations within 30 days prior to moderate to great earthquakes ($M \geqslant 5.0$), particularly during undisturbed day. Additionally, this study aims to evaluate the significance of the relationship between geomagnetic and TEC anomalies, with seismic activities, primarily for the 694 earthquakes with M $\geqslant$ 5.0 in the Japan region in 2011, through a detailed analysis of the temporal distribution of these disturbances. By utilising extensive databases such as SuperMag and GEONET, this study would be able to identify and assess temporal patterns of geomagnetic and TEC disturbances and thus address the limitations of prior studies concerning the reliability of space-based earthquake precursors.

2. Method

To obtain earthquake precursors with dual parameters from different layers of the Earth, it is necessary to monitor the daily variations in geomagnetic and TEC values both before and after seismic events. This study was divided into three (3) major parts: earthquake data selection, geomagnetic data processing, and TEC data processing. The first analysis involved filtering data to select earthquakes with M $\geqslant$ 5.0 over Japan were selected. Only data with the aforementioned characteristics were selected because of the potential damage intensity, as assessed by the United States Geological Survey (USGS). This requirement is necessary for data selection, as only earthquakes of higher magnitudes are capable of causing destruction; underscoring the importance of predicting their occurrence. However, in terms of depth, the study included only earthquake events with depths of not more than 200 km, as no events beyond this depth were recorded for the particular year in the study area. Details of the data processing and analysis of geomagnetic and TEC data are explained in the next section.

2.1. Data sets

The earthquake data for 2011 were acquired from the USGS (2024) database, based on selected criteria: a magnitude of not less than 5.0 and earthquake epicentres located within the earthquake preparation area, as defined by Dobrovolsky et al. (1979). In this study, earthquakes at all available depths were included in the analysis. The focus of this study on the year 2011 was because of the availability of data from the provider. The distribution of earthquake events within the year 2011 in the study area is depicted in Fig. 2. Data with temporal resolution of 1 min of global geomagnetic daily variations, recorded by global magnetometer stations during 2011, were downloaded and analysed from the SuperMAG database. Geomagnetic field data consisting of three components - north (N), east (E) and vertical (Z) - were used (Gjerloev, 2012). Information on the magnetometer stations used is provided in Table 1, and their locations are shown in Fig. 1. The TEC data acquired from the National Institute of Information and Communications Technology (NICT) with a 30-s temporal resolution were utilised in this study. The details of these stations are listed in Table 2, and their locations are shown in Fig. 1. These stations were chosen because they are located within the seismoactive regions and are capable of monitoring the effects of seismic activity for earthquake events studied. The global geomagnetic indices, ap and disturbance storm time (Dst), obtained from the NASA OMNIWeb Service, were also used in this study (NASA/GSFC, 2024). The period of observation for both the geomagnetic and TEC variations was 60 days before and five (5) days after each earthquake.

Table 1
Information on the magnetometer stations used in this study.

Station Code	Station Name	Latitude (∘N)	Longitude (∘E)
ASB	Ashibetu	43.460	142.170
ESA	Esashi	39.240	141.360
HTY	Hatizyo	33.120	139.800
KAG	Kagoshima	31.480	130.720
KAK	Kakioka	36.230	140.180
KNY	Kanoya	31.420	130.880
KUJ	Kuju	33.060	131.230
MIZ	Mizusawa	39.110	141.200
MMB	Memambetsu	43.910	144.190
MSR	Moshiri	44.370	142.270
ONW	Onagawa	38.430	141.470
PPI	Popov Island	42.980	131.730
RIK	Rikubetsu	43.480	143.760
YMK	Yamakawa	31.190	130.620

2.2. Geomagnetic analysis

This study employed the diurnal variation ratio (DVR) method to develop an observed variations for anomaly detection in geomagnetic variations. Although the DVR method used in this study required only limited temporal data, at least a pair of magnetometer stations were necessary to monitor the anomalies. Initially, all magnetometer stations with available data from the study area in 2011 were considered. However, only those stations with available data were included in the analysis. These stations were designated as ’near’ and ’far’ stations, where the ’near’ station is located at a distance of 190 km from the epicentre, and the ’far’ station is located between 600 km and 1000 km from the epicentre. This study followed the framework established by Hayakawa (2015) and Yusof et al. (2021), which have been widely used for determining the maximum acceptable epicentral distance. Hayakawa’s study indicated that the geomagnetic anomalies tend to be strongest within 200 km of the epicentre and diminish beyond 600 km, Similar distance thresholds have been applied in subsequent studies, reinforcing their reliability such as (Yusof et al., 2024; Wu et al., 2024). Applying established thresholds ensures comparability across different datasets and earthquake events. The epicentral distances for both magnetometer stations and GPS receivers were further defined for each method. The geomagnetic diurnal variation ratio, R, of the N, E, and Z-components were computed across all station pairs using the formula, where x represents the range of geomagnetic

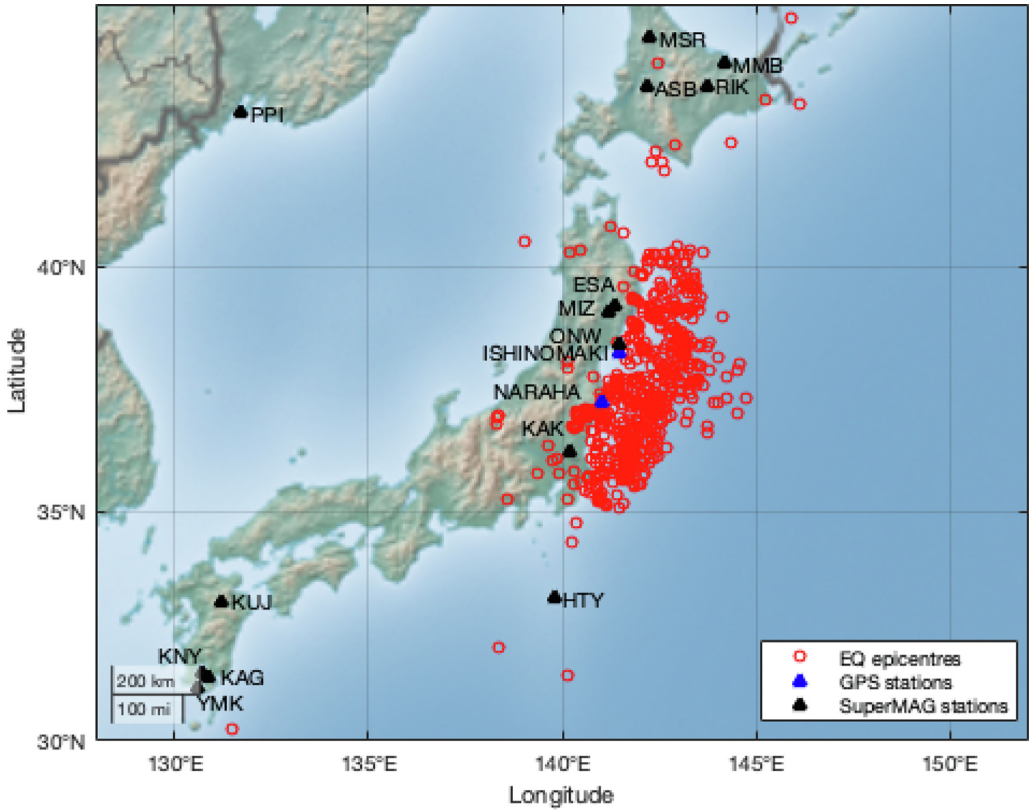


Fig. 1. Location of earthquake epicentres and geomagnetic and GPS stations studied.

Table 2
Information on the GPS stations used in this study.

Station Code	Station Name	Latitude (○N)	Longitude (○E)
0554	Ishinomaki	38.267	141.478
1011	Naraha	37.264	140.999

diurnal variations for each of the N, E, and Z- components, and is obtained by subtracting the minimum values from the maximum values of the geomagnetic diurnal variations at each near and far station.

$$R_x = \frac{\Delta x_{\text{near}}}{\Delta x_{\text{far}}} \quad (1)$$

Some data gaps occurred at certain stations on specific dates because of system malfunctions and human activity, resulting in no observations for these periods. The present study also integrated two global geomagnetic indices, namely, the ap and Dst indices. Specifically, the 3-h ap index, which is based on midlatitude observations, was considered. Additionally, the Dst index, which is capable of detecting all magnetic storms, was included in the analysis (Rostoker, 1972). Disturbed periods were identified based on daily values of ap exceeding 27 nT or Dst falling below −30 nT. An ap >27 nT corresponds to moderate to high geomagnetic activity (Veenadhari, 2006; Mourenas et al., 2019), while a Dst < −30 nT indicates a weak to moderate geomagnetic storm (Raja Halim Shah et al., 2024). These values were used to exclude disturbed periods to eliminate any external influences on the study. These thresholds have been widely used in similar studies, ensuring that the filtering method aligns with established research (Yusof et al., 2021; Yusof et al., 2024). Additionally, as a precautionary measure, the one-day period following a geomagnetic storm was also considered disturbed and was excluded from observation.

The impact of ionospheric currents on the geomagnetic Z-component was assessed by calculating a 15-day moving average of the geomagnetic diurnal variation ratio, later denoted as $\overline{\text{R}}$. Periods displaying unusual behaviour were classified as anomalies, as the influence of ionospheric currents typically lasts only a few days. Consequently, any daily value of the 15-day moving average of the geomagnetic diurnal variation ratio, $\overline{\text{R}}$, was deemed anomalous if it surpassed the threshold value, T, derived from the formula, where μ and σ represent the mean and standard deviation of R, respectively. In this research, a coefficient of k = 2 was selected. The value was considered based on the strength of the magnitude of the earthquakes included in the analysis of this study. Several other studies have employed the same value of k to detect geomagnetic and TEC disturbances, thereby ensuring comparability with prior work (Yusof et al., 2021; Yusof et al., 2024).

$$T = \mu_{\text{R}} \pm k\sigma_{\text{R}}(k = 2) \quad (2)$$

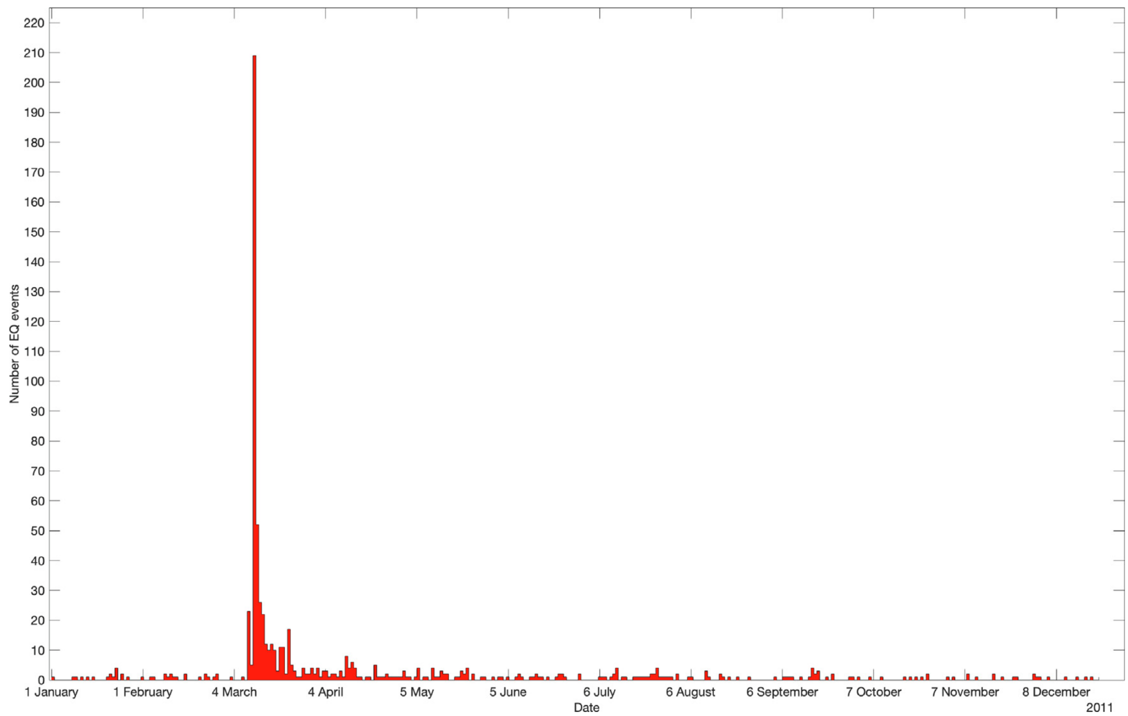


Fig. 2. Distribution of earthquake events throughout 2011 within the study area.

2.3. TEC analysis

To study the anomalies from the ionosphere, vertical TEC data from the GPS over Japan were extracted from the Global Navigation Satellite System Earth Observation Network of Japan (GEONET) network, acquired from NICT. All data were processed according to the methodology described by Otsuka et al. (2002). In this study, vertical TEC is referred to simply as TEC. Sharma et al. (2017) revealed that TEC concentration increases as the distance from the epicentre decreases. Based on these theories, the concept of earthquake preparation area was employed, using the formula established by Dobrovolsky et al. (1979), to calculate the spatial influence of the earthquake preparation area based on elastic deformation calculations, where r and M denotes the radius of the earthquake preparation area and the magnitude of the earthquake, respectively.

$$r = 10^{0.43M} \tag{3}$$

Only earthquakes occurring within the earthquake preparation area, as determined by their distance from the station, were analysed. The Dobrovolsky equation, which is widely used to estimate the influence radius of earthquake preparation zones and the associated ionospheric anomalies, has several limitations. One key limitation is the assumption that the strain field around the epicentre is uniform, which is often not the case in complex tectonic environments where stress distribution is highly heterogenous. Additionally, the equation does not account for variations in local geological and atmospheric conditions, which can significantly influence the strength and extent of ionospheric anomalies, therefore making a fixed influence radius potentially inaccurate for identifying earthquake-related ionospheric disturbances. The study then proceeded with earthquake declustering, based on Santis et al. (2019), to remove fore- and aftershock earthquakes. Both global geomagnetic indices, ap and Dst, were also used to filter out days with geomagnetic storms. This study utilised the moving median method to develop the observed variations for anomaly detection in TEC variations. The TEC daily variations before the earthquakes were analysed using the upper bound (UB) and lower bound (LB) method, which is computed based on the median, X, of TEC values for the past 30-day and the interquartile range, where UB and LB are the anomaly thresholds, X is the moving median, and IQR is the interquartile range, respectively.

$$UB = X + IQR \tag{4}$$

$$LB = X - IQR \tag{5}$$

These equations were used to detect TEC anomalies prior to the earthquakes (Sasmal et al., 2021; Sharma et al., 2010; Xia et al., 2011; Zhao et al., 2010). The 30-days window of moving median is commonly used in TEC anomaly detection study to represent the diurnal variation of typical monthly ionospheric variations. This duration reduces day-to-day variability and short-term fluctuations of TEC due to diurnal, seasonal and solar influences (Sharma et al., 2010; Tang et al., 2015; Tao et al., 2017). If the daily TEC variations exceeded either the upper or lower bound during the undisturbed day, it was considered an anomaly.

3. Results

In this section, the analysis of the results is divided into two parts: the first part focuses on the case study, while the second part addresses the regional study. The results of the selected events are presented in detail in Figs. 3–5, respectively. The results obtained from a comprehensive analysis of the relationship between the earthquake properties and geomagnetic and TEC anomalies before the earthquakes are presented in Fig. 6. The distribution of the total earthquake events studied are categorized by the presence of geomagnetic and TEC anomalies and are shown in Fig. 7.

3.1. Case study - selected events

Two earthquake events were selected as case studies to provide detailed examples of geomagnetic and TEC anomalies associated with earthquakes. The daily variations in the geomagnetic and TEC data are shown in detail in Figs. 3 and 5, respectively. From top to bottom, each panel shows the hourly values of the ap (magenta shades) and Dst (cyan shades) indices, while the temporal evolutions of $\overline{R}$ for each station's N, E and Z components are represented by different line colours in each corresponding panel. Daily TEC data were also plotted to show the occurrence of anomalies before the earthquakes.

3.1.1. 2011 M6.2 Namie, Japan Earthquake

For the M6.2 earthquake event which occurred on 19th August 2011 at 05:36:33 (UTC), and located approximately 61 kilometres east-northeast of Namie, Japan, the geographic coordinates of its epicentre were 37.671°N, 141.652°E, with a hypocentral depth of 47 km. Several anomalies, ranging from 60 days to two (2) days before the earthquake, are shown in Fig. 3. From Fig. 3, it is evident that anomalies were detected in both geomagnetic and TEC variations during undisturbed days. Anomalies appeared in both the E- and Z-components of geomagnetic variations. The anomalous variations in the E-component occurred over three days from 16th to 18th July (34 to 32 days prior to the earthquake), and in the Z-component for one day on 7th July (43 days prior to the earthquake). All anomalies were positive and showed increasing variations. The TEC variations were observed to have exceeded the upper bound and were deemed anomalous during the same period as the anomalous geomagnetic variations at both the Ishinomaki and Naraha stations from 14th to 18th July (36–32 days prior to the earthquake) and on 17th July (33 days prior to the earthquake), respectively. The anomalies at the Ishinomaki station displayed an increase of approximately 18 % to 50 % compared to the TEC value of an undisturbed day on 29th June at the Ishinomaki station, while at the Naraha

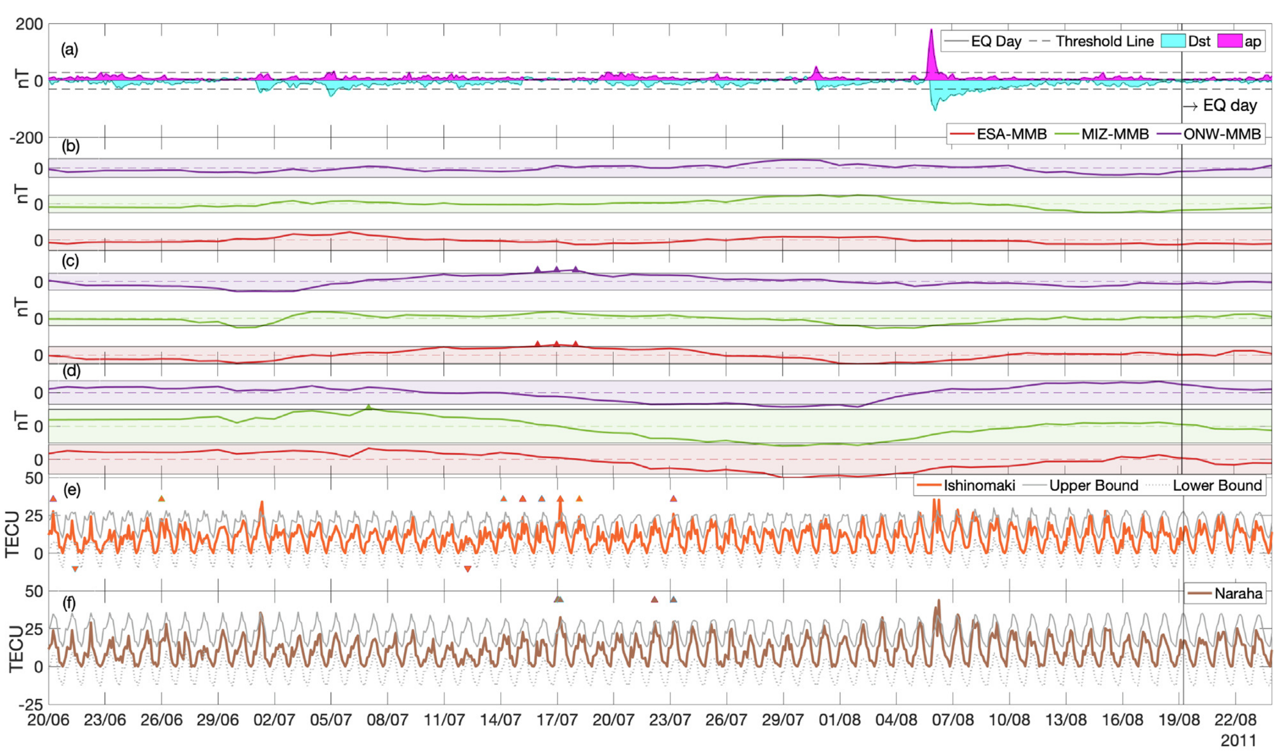


Fig. 3. The diurnal variations of geomagnetic and TEC parameters. Panel (a) illustrates the Dst and ap indices from 20th June to 24th August 2011. Panel (b) presents $\overline{R}$ values, for the N-component at stations ESA-MMB, MIZ-MMB, and ONW-MMB. Panel (c) displays $\overline{R}$ values, for the E-component at the same stations. Panel (d) shows the $\overline{R}$ values, for the Z-component at stations ESA-MMB, MIZ-MMB, and ONW-MMB. Panel (e) provides the TEC variations, along with their upper and lower bounds, for Ishinomaki station. Panel (f) presents the TEC variations, along with their upper and lower bounds, for Naraha station. The vertical line across the panels indicates the time of earthquake occurrence.

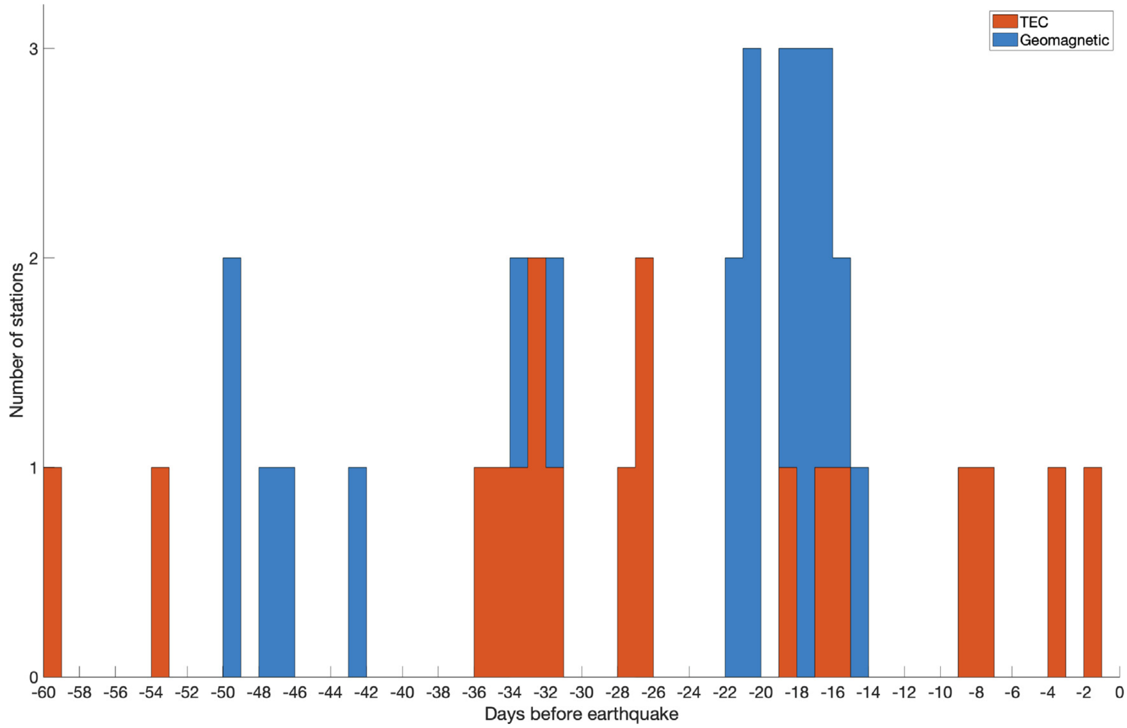


Fig. 4. Temporal variations of both geomagnetic and TEC precursors as detected across the number of stations.

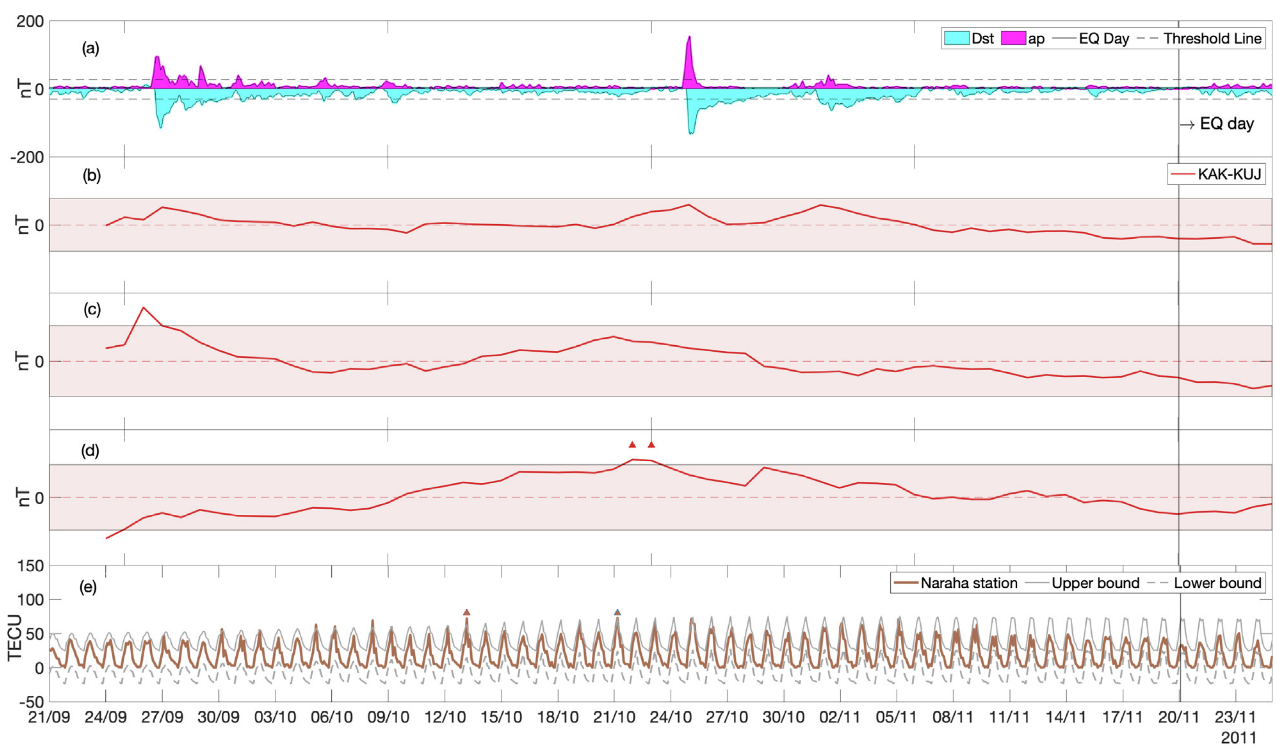
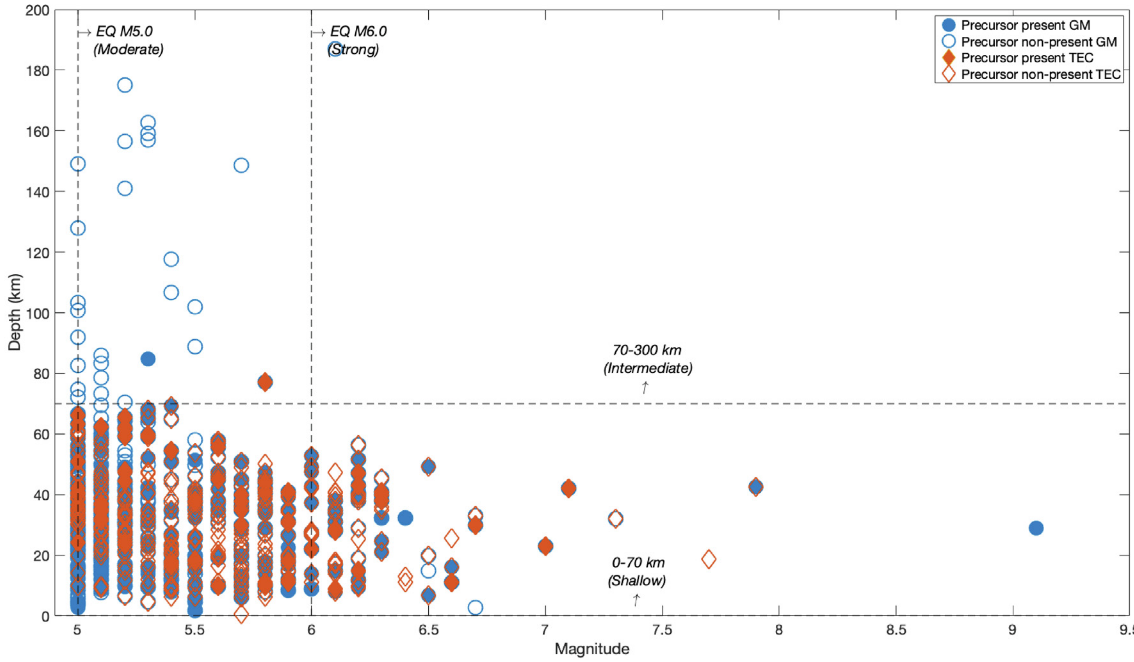
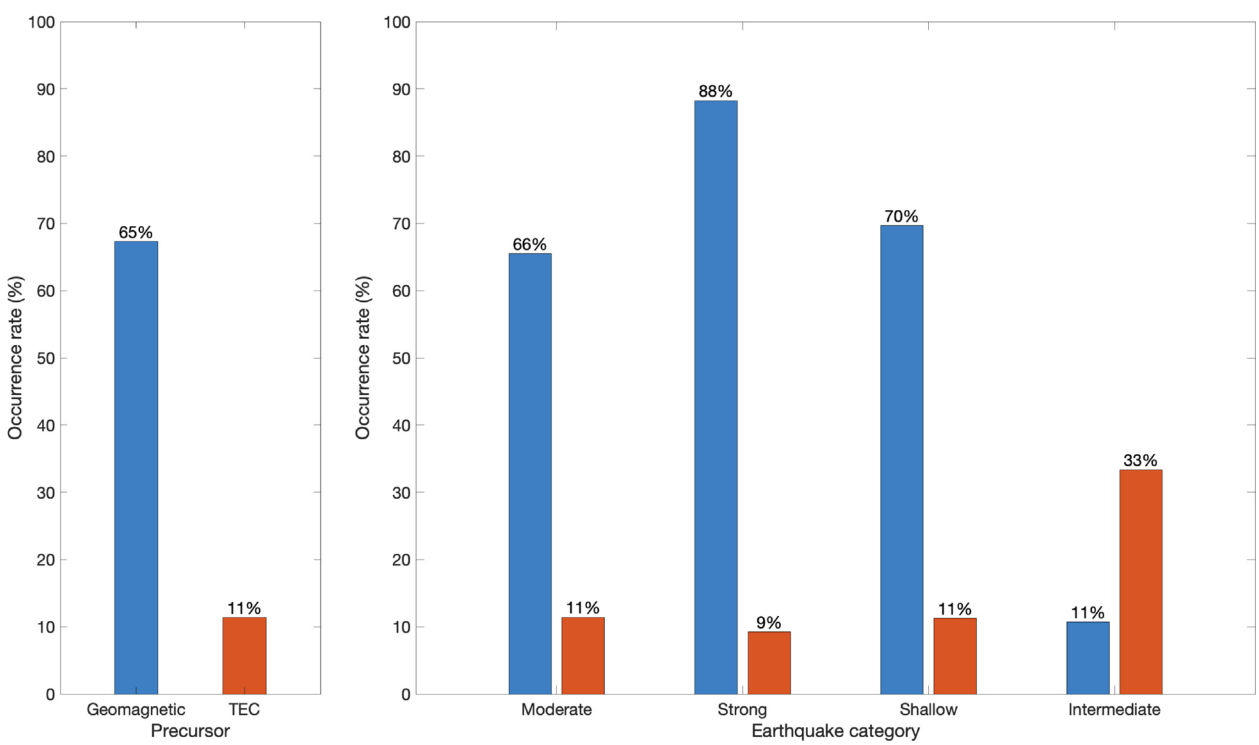


Fig. 5. The diurnal variations of geomagnetic and TEC parameters. Panel (a) presents the Dst and ap indices from 21st September to 25th November 2011. Panel (b) displays $\overline{R}$ values for the N-component at stations KAK-KUJ. Panel (c) shows $\overline{R}$ values for the E-component at the same stations. Panel (d) illustrates the $\overline{R}$ values for the Z-component at the stations KAK-KUJ. Panel (e) provides the TEC variations, along with their upper and lower bounds, for Naraha station. The vertical line across the panels indicates the time of earthquake occurrence.

station, the increase ranged from approximately 70 % to 130 %. When assessed relative to the IQR in upper and lower bound, the minimum percent change required to qualify as an anomaly ranged from approximately 44 % (20th June) to 89 % (26th June) for Ishinomaki station and, approximately 78 % (23rd July) to 147 % (17th July)



(a)



(b)

Fig. 6. (a) The distribution of geomagnetic and TEC precursors in terms of earthquake properties; depth, and magnitude. (b) The total occurrence rates of geomagnetic and TEC precursors, and their occurrence rates based on earthquake category.

for Naraha station. The minimum percent change from IQR was calculated by dividing the interquartile range (IQR) by the corresponding TEC median value (X) for each day and multiplying by 100, i.e., (IQR/ median TEC) × 100, which provides the minimum deviation percentage required for a TEC value to be considered anoma-

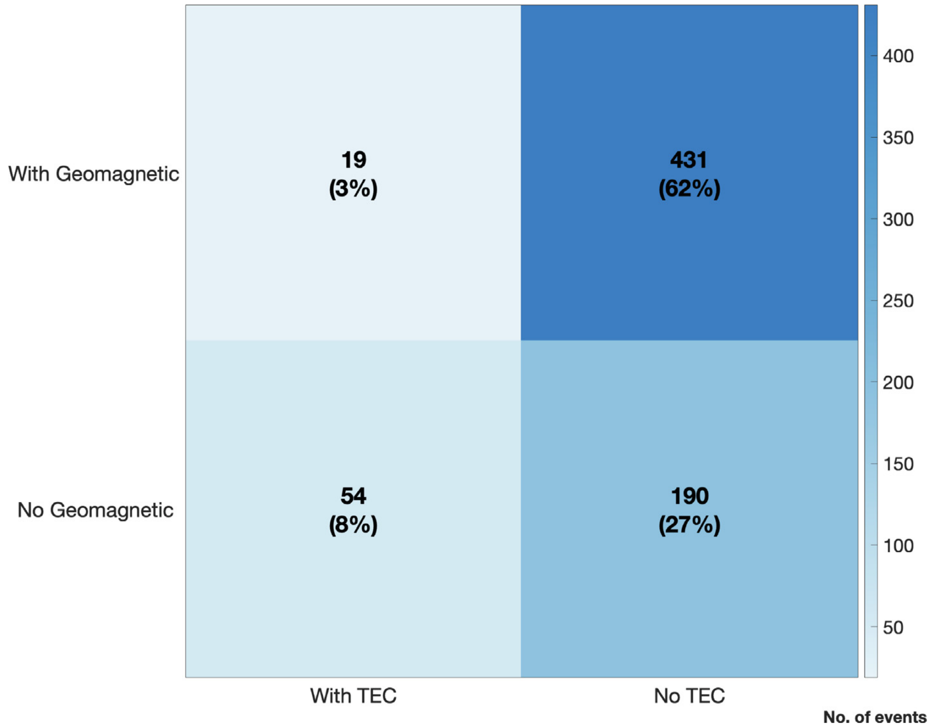


Fig. 7. Distribution of earthquake events (n = 694) categorized by the presence of geomagnetic and TEC anomalies for earthquakes in Japan for year 2011 with M $\geqslant$ 5.0. Each cell displays the number of events and their corresponding percentage. The majority of events (62 %) occurred with the presence of geomagnetic anomalies only.

lous based on upper and lower bound method as shown in formula (4) and (5).

To study the temporal behaviour of the anomalies for this event, the temporal variations of geomagnetic and TEC disturbances detected within the 60 days leading up to the day of the earthquake were compiled daily. Fig. 4 shows the daily temporal variations of the anomalies as detected across the total number of magnetometer and GPS stations. Both geomagnetic and TEC variations both showed anomalous behaviour during the first 60 days before the earthquake. It was observed that the precursors appeared earliest at 60 days and 50 days before the earthquake for geomagnetic and TEC anomalies, respectively. The highest number of stations detecting anomalies in geomagnetic variations occurred between 22 and 16 days prior to the earthquake, while TEC precursors were observed at 33 and 27 days before the seismic event. Concurrent anomalies in both geomagnetic and TEC variations were observed from one (1) month to two (2) weeks prior to the earthquake. These results are consistent with other studies, such as those by Yusof et al. (2021)), which also detected anomalies in geomagnetic variations within a month prior to the earthquakes. However, the results for TEC precursors in this study differ because previous studies detected these anomalies closer to the earthquake event, specifically three (3) days prior (Zulhamidi et al., 2023b).

3.1.2. 2011 M5.0 Daigo, Japan Earthquake

For the M5.0 earthquake event which occurred on 20th November 2011 at 01:23:44 (UTC), located approximately 2 kilometres to the east-northeast of Daigo, Japan, the geographic coordinates of its epicentre was positioned at the geographic coordinates of 36.775°N 140.378°E, with a hypocentral depth of 32 km. Several anomalies, ranging from 57 to 28 days prior to the earthquake, are presented in Fig. 5. Fig. 5 shows that anomalies occurred in both geomagnetic and TEC variations occurred during undisturbed days. The anomalies only appeared in the Z-component of the geomagnetic variations for two days from 22nd to 23rd October (29 to 28 days prior to the earthquake day). The anomalies during this period were positive and showed increasing variations. In contrast, TEC anomalies were observed one day before the anomalous period in geomagnetic variations on 21st October (30 days prior to the earthquake), showing an increase of approximately 35 % compared to the TEC value on the undisturbed day, which was 14th October, seven (7) days prior. Although these values significantly exceeded the baseline, their deviation from the upper bound was more modest, ranging from approximately 26 % (21st October) to 32 % (13th October), suggesting that while the anomalies were distinct, they were relatively close to the detection boundary.

3.2. Regional study

Earthquakes can be categorised based on their characteristics, including magnitude and depth, as reported by the California Earthquake Authority, CEA (2024) and Hayakawa (2015), respectively. Magnitudes classify the severity of earthquakes, ranging from moderate (M5.0 –

5.9), strong (M6.0-M6.9), major (M7.0–7.9), to great (M8.0 and higher). Depths, on the other hand, are categorised as shallow-focus (less than 70 km), intermediate depth or mid-focus (between 70–300 km), and deep focus (ranging from 300–700 km). These classifications are essential for understanding and assessing the impacts of earthquakes. The results obtained from this study showed the relationship and interaction of LAI coupling by monitoring geomagnetic and TEC variations 60 days before and five (5) days after the earthquake. Fig. 6 displays the occurrence rates of anomalies for all the earthquakes studied. The horizontal axis denotes the magnitude of the earthquake events, and the vertical axis represents the depth of the hypocentres. In the figure, the blue-filled circles indicate earthquake events with precursors present in the geomagnetic variations, the blank circles denote earthquake events with no precursors present in the geomagnetic variations, the orange-filled diamonds indicate earthquake events with precursors in the TEC variations, and the blank diamonds represent earthquake events with no precursors in the TEC variations.

From Fig. 6(a), it is evident that the analysis showed the rates of seismo-anomalies detected for geomagnetic and TEC variations were 65 % and 11 % of the total earthquakes studied, respectively. The presence of a geomagnetic precursor for strong earthquakes was 88 %, whereas that of the TEC precursor was 9 %. For moderate earthquakes, the geomagnetic precursor also showed higher presence, at 66 %, compared to only 11 %. Meanwhile, in terms of depth, 70 % of the shallow-focus earthquakes exhibited precursors in the geomagnetic variations, compared to 11 % in the TEC variations. The intermediate earthquakes showed a higher presence of TEC precursors (33 %), but only 11 % showed the presence of geomagnetic precursors. Based on Fig. 7 total of 19 earthquakes (3 %) exhibited anomalies in both TEC and geomagnetic data, indicating a relatively small subset of events with simultaneous precursor signals in both parameters. In contrast, a much larger number of earthquakes showed anomalies in only one of the two, specifically, 431 events (62 %) had geomagnetic anomalies without TEC anomalies, while 54 events (8 %) showed TEC anomalies without geomagnetic disturbances. This highlights that geomagnetic anomalies were more frequently observed than TEC anomalies in this dataset. Meanwhile, 190 events (27 %) did not exhibit any detectable anomalies in either parameter. These findings suggest that while simultaneous TEC and geomagnetic precursors are rare, the presence of anomalies in at least one parameter occurs in a significant proportion of events, supporting the relevance of dual-parameter analysis in earthquake precursor studies. Overall, the results indicate a higher occurrence of precursors in geomagnetic variations. Precursors are more likely to be found in earthquakes with higher magnitudes and within shallow geomagnetic variations.

The results are in agreement with the findings of Zulhamidi et al. (2023a), where intermediate-depth earthquakes were found to produce higher rates of precursors presence compared to shallow depth earthquakes, while moderate earthquakes yielded better results than strong earthquakes for TEC variations. Hypothetically, the farther the distance of the earthquake's focus point from the surface, the lower the rate of precursors presence, as the hypocentre, being farther from the magnetometer might result in greater signal attenuation. Despite these counterintuitive findings, they could be supported by the well-established theory of seismo-electromagnetic generation through the electrification process (Hayakawa, 2015). According to Reynard et al. (2010), shallow and intermediate-focus earthquakes, which occur in depths with different mineralogical compositions could influence electrification and affect the rate of precursors presence. The higher frequency of TEC precursors in intermediate-depth earthquakes is likely due to the ionospheric disturbance propagation effects and local geological and tectonic factors. These intermediate-depth earthquakes are capable of generating strong electromagnetic emissions that propagate efficiently into the upper atmosphere and ionosphere. These particles travel upward with less dissipation than in shallow earthquakes, where energy is absorbed near the surface. Certain subduction zones and fault structures associated with intermediate-depth earthquakes may induce strong LAI interactions, thereby enhancing the TEC detection of TEC anomalies. This finding suggests that depth-dependent factors must be considered in TEC-based earthquake precursor studies.

4. Discussion

Monitoring of geomagnetic and TEC variations to identify the pre-seismic anomalies as earthquake precursors is challenging due to the possibility of the presence of false positives, as there are instances where anomalies appeared before the seismic event but may not be related to the seismic activity. To distinguish the seismic effects from other influences, several approaches were implemented, including filtering out disturbed days based on geomagnetic indices such as ap and Dst to mitigate the influence of solar activity. Incorporating additional space weather indices, such as sudden ionospheric disturbances index or the solar activity index such as F10.7, could enhance the isolation of seismic-related anomalies. Moreover, integrating different parameters, including ground-based measurements and satellite data, could be used to differentiate between seismic-related signals and artificial signals, such as radio-frequency interference, satellite transmissions, and human-made ionospheric modifications. For example, the 2011 M6.2 Namie, Japan earthquake event discussed in Section 3.1.1 showed TEC anomalies detected from 60 days to 2 days before the earthquake, but only several dates were considered as precursors since the anomalies occurred during the disturbed days, and several others did not coincide with geomagnetic anomalies.

In the case study, the TEC anomalies were detected earlier than those reported in previous studies. For instance, Sharma et al. (2010) observed the TEC anomalies from 3 days to 1 days before the earthquake, while Tao et al. (2017) detected the TEC anomalies 2 days before the earthquake. This discrepancy can be attributed to differences in detection methodologies. The longer observation period compared to previous studies could have detected anomalies that might have been overlooked in shorter-duration analyses. The absence of a universally accepted preseismic monitoring time frame further increases the challenge of distinguishing true precursors from natural ionospheric variability, thereby increasing the uncertainty in anomaly characterisation.

In addition to being detected earlier than in previous studies, TEC anomalies were also observed before geomagnetic anomalies in the case of the 2011 M5.0 Daigo, Japan earthquake, as discussed in Section 3.1.2. This occurrence suggests variations in how disturbances propagate through the LAI coupling process. It is possible that TEC changes are triggered by seismo-ionospheric coupling, where the electron density in the ionosphere is enhanced before strong geomagnetic effects are observed. The electric field coupling from the earthquake preparation zone may travel upward to the ionosphere faster than the cumulative build-up of geomagnetic disturbances. This phenomenon is also discussed in Yusof et al. (2021), where it was observed that the direct lithospheric effects that cause geomagnetic anomalies were more localised and detectable over shorter distances. Beyond these physical mechanisms, the observed results may also be influenced by the differences in the sensitivity of TEC and geomagnetic field measurements. TEC data may have a higher temporal resolution and sensitivity, allowing for the early detection of small-scale ionospheric changes. In contrast, geomagnetic field variations may require a stronger cumulative seismic disturbance to become noticeable, leading to a delayed response in geomagnetic records. It should be emphasized, however, the early detection for TEC anomalies is highly dependent on the detection method employed. The sequence of these events may vary across different cases, and while TEC anomalies might serve as an earlier earthquake precursor in some instances, further investigations are needed to confirm the precursory behaviour of this parameter.

Despite the physical mechanisms described above, TEC variations can result from both natural factors and earthquake-related disturbances. Normal fluctuations in TEC are influenced by solar activity, diurnal cycles, seasonal changes, and latitude dependence. Therefore, isolating seismo-ionospheric signals requires careful consideration of these factors. Additionally, the sample was found to exhibit a bias concerning both magnitude and depth, indicating a tendency for certain magnitudes and depths to be overrepresented or exhibited, thereby influencing the overall representation and leading to an imbalance in the findings. To comprehensively explore the coupling of LAI with seismic activities, it is essential to undertake a more detailed analysis that encompasses a broader array of earthquake cases in the future. This expanded analytical approach will contribute to a deeper understanding of the complex relationships and potential influences between geophysical phenomena and seismic events, thereby providing valuable insights for advancing our knowledge in this interdisciplinary field.

5. Conclusion

In this study, the geomagnetic and TEC variations for the 60 days preceding and five (5) days following the occurrence of 694 earthquakes with magnitudes of $M \geqslant 5.0$ were investigated to assess the significance of the relationship between geomagnetic and TEC disturbances and seismic activities. Our results reveal a significant correlation exists between geomagnetic and TEC disturbances and seismic activities, particularly in the 60 days prior to an earthquake. The results suggest that both types of disturbances could potentially serve as useful indicators for earthquake prediction and mitigation efforts. One of the more significant findings of this study is that the geomagnetic precursors occurred at a higher rate of 65 % than TEC precursors (11 %), although there were cases where both types of precursors could be detected before an earthquake event (3 %). Notably, anomalies from both parameters were detectable up to a month before the earthquake.

Other sources contributing to geomagnetic and ionospheric disturbances were also discussed in this study, with both precursors correlated with earthquake properties such as magnitude and depth. Both geomagnetic and TEC precursors were significantly found in moderate and shallow earthquakes, reflecting the scarcity of events at higher magnitudes and depths. In conclusion, this study provides valuable insights into the relationship between geomagnetic and TEC variations and seismic activities, which could have important implications for earthquake precursors and disaster mitigation efforts. This study attempts to establish a connection between the effects of earthquakes across multiple layers of the Earth. Future research could integrate other parameters, such as surface deformation, by analysing the radar images using interferometric synthetic aperture radar (InSAR) method to further investigate and substantiate the relationship between earthquakes and LAI coupling.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Akpan, A.E., Ibanga, J.I., George, N.J., et al., 2024. Assessing seismo-ionospheric disturbances using Vanuatu and Honshu earthquakes of March 25, 2007, employing DEMETER and GPS data. Int. J. Environ. Sci. Technol. (Tehran) 16 (11). https://doi.org/10.1007/s13762-019-02339-x.

CEA, 2024. How are earthquakes measured? Magnitude & intensity scales.https://www.earthquakeauthority.com/blog/2020/earthquake-measurements-magnitude-vs-intensity.

Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the size of earthquake preparation zones. Pageoph 63 (7), 117.

Dong, Y., Gao, C., Long, F., et al., 2022) Suspected seismo-ionospheric anomalies before three major earthquakes detected by gims and gps tec of permanent stations. Remote Sens., 14(1).https://www.mdpi.com/2072-4292/14/1/20.

Fagundes, P.R., Pillat, V.G., Tardelli, A. et al., 2024. Pole-to-pole ionospheric disturbances due to solar flares, during low solar activity. J. Geophys. Res.: Space Phys., 129(7), e2024JA032597.https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2024JA032597. arXiv: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2024JA032-597. E2024JA032597 2024JA032597.

Gjerloev, J.W., 2012. The supermag data processing technique. J. Geophys. Res.: Space Phys. 117 (9).

Hasbi, A., Mohd Ali, M., Misran, N., 2011. Ionospheric variations before some large earthquakes over sumatra. Nat. Hazards Earth Syst. Sci. 11 (2), 597–611.

Hayakawa, M., 2015. Earthquake prediction with radio techniques. doi:10.1002/9781118770368.

Hayakawa, M., Izutsu, J., Schekotov, A. et al., 2021. Lithosphere-atmosphere-ionosphere coupling effects based on multiparameter precursor observations for February-March 2021 earthquakes (m 7) in the offshore of Tohoku area of Japan. https://www.mdpi.com/journal/geosciencesGeosciences2021,11,481. doi:10.3390/geosciences.

Mourenas, D., Artemyev, A., Zhang, X.-J. et al., 2019. Extreme time-integrated geomagnetic activity: Ap index statistics. https://arxiv.org/abs/1901.09823. arXiv:1901.09823.

Naaman, S., Alperovich, L.S., Wdowinski, S., et al., 2001. Comparison of simultaneous variations of the ionospheric total electron content and geomagnetic field associated with strong earthquakes. Nat. Hazards Earth Syst. Sci. 1 (1/2), 53–59. https://doi.org/10.5194/nhess-1-53-2001, URL: https://nhess.copernicus.org/articles/1/53/2001/.

NASA/GSFC, 2024. Omniweb data explorer.https://omniweb.gsfc.nasa.gov/form/dx1.html.

Otsuka, Y., Ogawa, T., Saito, A., et al., 2002. A new technique for mapping of total electron content using gps network in Japan. Earth Planets Space 54, 63–70.

Pulinets, S., Boyarchuk, K., 2004. Ionospheric Precursors of Earthquakes. Springer, Berlin, Heidelberg. https://doi.org/10.1007/b137616.

Pulinets, S., Kotsarenko, A., Ciraolo, L. et al., 2007. Special case of ionospheric day-to-day variability associated with earthquake preparation. Adv. Space Res., 39(5), 970–977.https://www.sciencedirect.com/science/article/pii/S0273117706004406.

Raja Halim Shah, R.A., Abdul Hamid, N.S., Abdullah, M., et al., 2024. A comprehensive classification and analysis of geomagnetic storms over solar cycle 24. Res. Astron. Astrophys. 24 (8), 085007. https://doi.org/10.1088/1674-4527/ad5b34.

Reynard, B., Nakajima, J., Kawakatsu, H., 2010. Earthquakes and plastic deformation of anhydrous slab mantle in double wadati-benioff zones. Geophys. Res. Lett., 37, 24309.https://hal.archives-ouvertes.fr/hal-00681333. doi:10.1029/2010GL045494.

Rostoker, G., 1972. Geomagnetic indices. Rev. Geophys. Space Phys. 10, 935–950.

Santis, A.D., Marchetti, D., Pavón-Carrasco, F.J., et al., 2019. Precursory worldwide signatures of earthquake occurrences on swarm satellite data. Scient. Rep. 9. https://doi.org/10.1038/s41598-019-56599-1.

Sasmal, S., Chowdhury, S., Kundu, S., et al., 2021. Pre-seismic irregularities during the 2020 samos (Greece) earthquake (m = 6.9) as investigated from multi-parameter approach by ground and space-based techniques. Atmosphere 12. https://doi.org/10.3390/atmos12081059.

Sharma, G., ray, P.K.C., Mohanty, S., et al., 2017. Ionospheric tec modelling for earthquakes precursors from gnss data. Quatern. Int. 462, 65–74. https://doi.org/10.1016/j.quaint.2017.05.007.

Sharma, K., Dabas, R.S., Sarkar, S.K., et al., 2010. Anomalous enhancement of ionospheric f2 layer critical frequency and total electron content over low latitudes before three recent major earthquakes in china. J. Geophys. Res. 115.

Tang, J., Yao, Y., Zhang, L., 2015. Temporal and spatial ionospheric variations of 20 April 2013 earthquake in Yaan, China. IEEE Geosci. Remote Sens. Lett. 12 (11), 2242–2246. https://doi.org/10.1109/LGRS.2015.2463081.

Tao, D., Cao, J., Battiston, R., et al., 2017. Seismo-ionospheric anomalies in ionospheric tec and plasma density before the 17 July 2006 *m*7.7 south of java earthquake. Ann. Geophys. 35 (3), 589–598. https://doi.org/10.5194/angeo-35-589-2017, URL: https://angeo.copernicus.org/articles/35/589/2017/.

Tao, D., Wang, G., Zong, J., et al., 2022. Are the significant ionospheric anomalies associated with the 2007 great deep-focus undersea Jakarta–Java earthquake?. Remote Sens. 14 (9).

Tsugawa, T., Saito, A., Otsuka, Y., et al., 2011. Ionospheric disturbances detected by gps total electron content observation after the 2011 off the pacific coast of Tohoku earthquake. Earth, Planets and Space 63 (7), 875–879.

USGS, 2024. Search earthquake catalog.https://earthquake.usgs.gov/earthquakes/search/.

Veenadhari, B., A, S., 2006. Space weather effects on low latitude geomagnetic field and ionospheric plasma response.

Wu, F., Yao, D., Yu, C., 2025. An investigation into the influence of solar flares and geomagnetic storms on the f2 layer of the ionosphere in western europe during March 2024. Adv. Space Res., 75(1), 936–952. https://www.sciencedirect.com/science/article/pii/S0273117724009475. doi: 10.1016/j.asr.2024.09.027.

Wu, Z., Xia, J., Tan, B. et al., 2024. Detection and characterization of geomagnetic anomaly waveforms. J. Asian Earth Sci., 259, 105837. https://www.sciencedirect.com/science/article/pii/S1367912023002985. doi: 10.1016/j.jseaes.2023.105837.

Xia, C., Wang, Q., Yu, T., et al., 2011. Variations of ionospheric total electron content before three strong earthquakes in the Qinghai-Tibet region. Adv. Space Res. 47, 506–514. https://doi.org/10.1016/j.asr.2010.09.006.

Yaso, N., Hasbi, A.M., Abdullah, M., 2013. Investigation of ionospheric response due to tohoku earthquake using gps satellite measurements. In: Proc. IconSpace Conf, pp. 88–91.

Yusof, K.A., Abdullah, M., Abdul Hamid, N.S., et al., 2021. Statistical global investigation of pre-earthquake anomalous geomagnetic diurnal variation using superposed epoch analysis. In: IEEE Trans. Geosci. Remote Sens., pp. 1–13.

Yusof, K.A., Mashohor, S., Abdullah, M., et al., 2024. Earthquake prediction model based on geomagnetic field data using automated machine learning. IEEE Geosci. Remote Sens. Lett. 21, 1–5. https://doi.org/10.1109/LGRS.2024.3354954.

Zhao, B., Wang, M., Yu, T., et al., 2010. Ionospheric total electron content variations prior to the 2008 Wenchuan earthquake. Int. J. Remote Sens. 31, 3545–3557. https://doi.org/10.1080/01431161003727622.

Zulhamidi, N.F.I., Abdullah, M., Abdul Hamid, N.S., et al., 2023a. Comparative analysis of variants of geomagnetic diurnal variation ratio method for earthquake precursor detection. Jurnal Kejuruteraan 35 (4), 881–888.

Zulhamidi, N.F.I., Abdullah, M., Abdul Hamid, N.S. et al., 2023b. Investigating short-term earthquake precursors detection through monitoring of total electron content variation in ionosphere. Front. Astron. Space Sci., 10.https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2023.1166394.