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ORIGINAL PAPER

# Assessing seismo-ionospheric disturbances using Vanuatu and Honshu earthquakes of March 25, 2007, employing DEMETER and GPS data

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## Abstract
The signals of detection of electromagnetic emissions transmitted from earthquake regions (DEMETER), plasma ion analyser, instrument *Sonde de Langmuir* sensors, global positioning system and total electron content (TEC) were used to decipher variations of electron and ion density in the neighbourhoods of twin seismic events. These events took place on March 25, 2007, at Vanuatu and Honshu (Japan). Investigations through statistical analysis revealed that ionospheric plasma parameters of electron density and ion density were disturbed on both sets of data on the 6th and 4th days before the Honshu earthquake in Japan, during quiet geomagnetic period. However, for the Vanuatu earthquake, all detected irregularities from DEMETER data occurred during geomagnetic storm. Nevertheless, TEC anomaly showed unusual variations exactly two weeks before the seismic activity on quiet geomagnetic day. The disturbance storm time and planetarische Kennziffer indices were engaged in isolating pre-earthquake irregularities from other irregularities associated with geomagnetic actions.

**Keywords** Earthquakes · Anomaly · Seismo-electromagnetic perturbations · Vanuatu and Honshu

## Introduction

Generic natural processes, such as seismic sea waves, perturbation of geomagnetic activities and seismo-electromagnetic associated anomalous phenomena abound, are generally considered as potential quasi-precursors of earthquakes. Earthquakes occur prior to electromagnetic perturbations, and it is believed that this seismo-electromagnetic variance is a reflection of various processes that started several days afore the earthquake day and subsist some days after its occurrence (Ibanga et al. 2017). Micro-fracturing of earth's crust is viewed to be caused by the generation of seismo-electromagnetic anomaly (Schwingenschuh et al. 2011). The rising of water under the earth surface plus astronomical rise in the outflow of radon precede the occurrence of earthquake, and consequently, the conductivity of the troposphere gets elevated by reason of increased ionisation by radon sources. Generally, preliminary and post-seismo-electromagnetic anomalies in extremely low frequency/very low frequency amplitude along with atmospheric factors are described from satellite-based explanations surrounding earthquakes (Friedrich and Rapp 2009) The variations in the atmospheric parameters are directly linked to seismo-electromagnetic activities, which, in turn, are related to the coupling processes of the lithosphere and atmosphere (Martynenko 1989; Fuks et al. 1997; Pulinets and Ouzounov 2011). The survey of seismo-electromagnetic occurrences confirms the elevation of direct current electric field associated with the creation of cyclic inhomogeneous flow of electrical conductivity from lower ionosphere besides the development of geomagnetic field-aligned plasma layer in the higher atmosphere. The electrical conductivity caused by direct current electric field in ionosphere prior to earthquake initially provokes the production of quasi-periodic horizontal inhomogeneities in the conductivity of the ionosphere. The perturbations experienced in the lower ionosphere are characteristically caused by electromagnetic fields of extensive current system in the terrestrial core at the concluding stage of earthquake generation. Documented literatures show that

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before a seismic event occurs, a significant deviation in the electric field, which alters the direction of the field near the surface, is noticed (Martynenko 1989; Fuks et al. 1997; Akhoondzadeh et al. 2010). Consequently, changes in electric field amplitudes are significantly noticed in the lower part of the ionosphere. This imbalance induces alterations in the lower atmospheric quantities. The changes associated with atmospheric factors are mirrored through electron concentration, electron-neutral collision frequency, attachment and detachment frequency, electron temperature, etc. Thus, a possible coupling mechanism for the lithosphere–ionosphere interaction resulting in earthquake can be determined using anomalous behaviours deciphered from the analyses of ion density, electron density, and electron temperature. Electron-neutral collision frequency is the utmost quantity that is affected by the electric field generated during earthquake. In this study, the analyses of these dynamic tools that give the details of the seismo-electromagnetic events afore and after the March 25, 2007, Earthquakes of Vanuatu and Honshu (Japan) are principally considered.

## Data

### Data from DEMETER satellites

Distant satellites like DEMETER could be used to study the upper part of ionosphere. The DEMETER is principally known among other uses to be scientifically excellent in detecting anomalous perturbations of electromagnetic waves, thermal plasma parameters, and fluxes of particles that may be linked to seismic activity. DEMETER trajectory having a height of about 710,000 m is known to be spherically polar, and closely synchronous with sun. Two different local times corresponding to 10:30 and 22:30 were selected as the kernel for quantifications. Streams of plasma waves and energetic particle fluxes, available from DEMETER, can be assessed for study continuously. Four electrical analyses that used sensor of electrical field strength (ICE) measured the three associated components of the electric field using a frequency window of DC that was up to 3.5 MHz. The search coil (IMSC) of magnetometer measured the interesting three constituents of field of magnet in a frequency window, which spans from few Hz to 20 kHz. Plasma wave analyser (IAP) detected density of ion configuration, temperature, and the flow speed. Two sets of Langmuir probes sensors (ISL) enabled assessments temperature and density of electron. The detector of solid and energetic particle (IDP) recorded elevated energy of electrons and high protons. Generally, the two known modes of operations in practice are the survey mode, which is used in recording the low bit rate data in the vicinity of the Earth at invariant latitudes, which is less than 65 degree, as well as the burst mode, which records elevated bit rate data that are above areas with seismic events (Akhoondzadeh et al. 2010).

The ISL and IAP experimental data of the burst mode used in this study to enable the assessments of the ionospheric disturbances associated with two earthquakes of March 25, 2007. The Vanuatu Island earthquake had magnitude 7.1 and occurred at 0.40 Universal Time Coordinate (UTC) while at about 0:41 h in Honshu (Japan), earthquake with magnitude 6.7 occurred. ISL was aimed to record the plasma electron density in an array of $10^8$ to $5 \times 10^{11}$ $m^{-3}$; electron temperature in the limit of 600–10,000 K and the signal potential of the satellite also falls within the range of $\sim \pm 3$ V. In all, disparities in these factors were achieved with a time resolution of 1 s according to the work of Lebreton et al. (2006). Paramount objective employed in IAP device was tailored towards making possible measurements of the core factors of the thermal population or densities of the key ions of the ionosphere. These ions are $H^+$, $He^+$ and $O^+$ in a span of $10^2$ to $5 \times 10^5$ ions $cm^{-3}$. Ionic temperatures ranged from 500 to 5000 K, while according to Berthelier et al. (2006), the flow of ion velocity harmonises with the frame of reference of the earth. By using the web server (http://DEMETER.cnrs-orleans.fr) according to (Akhoondzadeh et al. 2010), data and some functional plots can be accessed when using half-orbits from (http://DEMETER.cnrs-orleans.fr). The ISL and IAP physical records, belonging to these orbits were selected and evaluated. Data for this study with regard to the time and geographic location as well as magnitudes of earthquakes were selected from the locations near the satellite. This was done 30 days before and 10 days after the seismic activity.

### GPS total electron content (TEC) data

Measurements of natural perils, such as earthquakes, have been successful through the GPS satellites. The huge web of GPS receivers (few of thousands of GPS TEC data, in the planet) projects the real-time and high temporal resolution in terms of the scale of universal coverage. TEC disparity distributions are investigated using seismo-ionospheric precursors associated with the global TEC data analysis, continuous observation and achievable satisfactory time- and space-resolution in addition to the availability of large volume of data. The satellite of GPS transmits dual signal frequencies (LI = 1575.42 MHz and L2 = 1227.60 MHz).These sets of GPS receivers detect ionospheric TEC disorders resulting from the surface generation of Rayleigh, acoustic and gravity wave signals. TEC is comfortably defined as the integrated of entire number of electrons along a path from the receiver to each GPS. Evaluation of spatial sizes and temporal variations in the pre-earthquake ionospheric effects in any seismogenic area can be achievable using TEC. The TEC index is conspicuously linked with high density in the F-layer, which is larger than what is obtainable in the other layers (Sunil et al. 2015). TEC makes it possible for the desertion of acoustics, gravity, or both types of wave perturbations within the upper atmosphere. Calais and Minster (1995) used the TEC technique to identify the disturbance/perturbation caused by earthquakes. Zaslavski et al. (1998) also employed a numerical approach with TEC data obtained from TOPEX–POSEIDON to establish the link existing between ionospherically induced perturbations and seismic activities. Ionospheric TEC information from a network of GPS was estimated by Liu et al. (2002) statistically in Taiwan. Earthquake process has deformed the surface of the earth due to the accumulation of strain and slips over time. According to (Celebi et al. 2012), GPS is often utilised to screen this move by determining accurately the station that is at most 5 mm of areas closed to active faults, which are relative to each other. GPS has an altitude of about 20,000 km, and it has a composition of satellites, which orbit the earth twice daily.

### Geomagnetic data

It is important to note that the ionospheric conditions are influenced by solar geophysical conditions and geomagnetically induced storms particularly in the Polar and equatorial regions, where equatorial electrojets and auroral activities are significant. These geomagnetic perturbations give rise to what is known as mid-latitude ionospheric disturbances. Conversely, equatorial storm time and ionospheric current ring current in eras of solar-terrestrial disturbances generate substantial perturbation in the geomagnetic field detected on the ground surface. The observed parameters may present anomalous changes even when there is no seismic event. Hence, it is challenging to segregate pre-seismic ionospheric processes from the ionospheric perturbations due to the solar-terrestrial events (Ondoh 2008; Akhoondzadeh et al. 2010). In view of this, to classify the seismo-ionospheric disturbances emanating from disorders of geomagnetism, the geomagnetic indices Dst and Kp (www.gfz-potsdam) have to be checked (Akhoondzadeh et al. 2010). The Kp index checks for the planetary event on a world-wide sense, while the index of Dst records the equatorial ring current changes according to Mayaud (1980) and Akhoondzadeh et al. (2010). The influence of ionospheric geomagnetic storm has a universal effect, which is being witnessed in a global scale, while the effect of seismogenic events is detected only within a distance which is not greater than 2000 km in relation to the prospective epicentre (Pulinets et al. 2003). It is worthwhile to note that the geomagnetic storm of the ionosphere typically takes between 8 and 48 h, while the seismo-ionospheric turbulences have period ranging from 3 to 4 h, in a few days to the earthquake as specified by Pulinets et al. (2003), Akhoondzadeh et al. (2010), Pulinets and Boyarchuk (2004) and Gousheva et al. (2008).

## Materials and methods

This work is based on the described geographic latitude and longitude data for seismic activity of the chosen epicentre in Vanuatu and Honshu. The orbits of DEMETER satellites selected in the study area considered the ionospheric parameters 30 days prior to earthquake and 10 days after the earthquake according to the earthquake magnitude.

Radius of this zone from the epicentre was projected using the Dobrovolsky et al. (1979) formula;

$$R = 10^{0.43M} \tag{1}$$

where $R$ represents the radius of the earthquake's preparation zone, and $M$ is the earthquake's magnitude. According to Akhoondzadeh et al. (2010) perturbations in the concentration of electron are noticed when the ground surface associated with anomalous field in the study area exceeds 200,000 m in diameter. Moreover, it is also asserted that majority of the area influenced by the ionosphere does not agree with the vertical estimation of the epicentre of the imminent earthquake. However, it is tending towards the equator in the regions considered to have high and middle latitudes (Pulinets et al. 2003). Consequently, it is practicable to analyse the recorded in the satellite orbits near the epicentre afore the earthquake days. Based on this notion, optimum values of distances between the satellite and epicentre were chosen according to DEMETER satellite height and radius of earthquake zone. Searching for earthquake anomaly from ionospheric variations requires the determination of a reasonable range of ionospheric regular variations, which make some models (e.g. IRI-2000) available for short- and long-term predictions of ionospheric parameters according to Bilitza (2001) possible. This reflects that the variation from the predicted models and the measured data can be used to record the anomaly in earthquake surveys. However, the experimental results from the models will always deviate from measurements even at the period of quiet conditions. The low sensitivity of these models to detect fast changes in ionosphere during solar and geomagnetic activity can be used to justify the irregularity (Akhoondzadeh et al. 2010). Bolzan et al. (2009) used variability in time of the main periodicities of intermittent processes during a geomagnetic storm to enhance the efficiency of the models through wavelet transform. This shows that it is important to undertake detailed analyses of intermittent and non-intermittent events in ionosphere that leads to variations provoked by a seismic electric domain. The application of statistical analyses employing the median ($M$) and the inter-quartile range (IQR) of acquired data is used to figure out the upper and lower bounds. This is necessary to separate seismic perturbations from the natural variation backgrounds (Liu et al. 2004; Akhoondzadeh et al. 2010). The statistical parameters considered in the calculations were selected to cover the duration of about 40 days in order to annul the effect of periodic changes. The upper and lower limits observed have range according to Akhoondzadeh et al. (2010) as in Eqs. 2 and 4:

$$X_{\mathrm{H}} = M + y \cdot \mathrm{IQR} \tag{2}$$

$$X_{\mathrm{L}} = M - y \cdot \mathrm{IQR} \tag{3}$$

$$X_{\mathrm{L}} < X < X_{\mathrm{H}} \Rightarrow -y < \frac{X - M}{\mathrm{IQR}} < y; \quad D_X = \frac{X - M}{\mathrm{IQR}} \tag{4}$$

where $X$ represents parameter value, $X_{\mathrm{H}}$ represents upper bound, $X_{\mathrm{L}}$ represents lower bound, Dx differential of $X$, and $y$ an arbitrary reference level. Consequently where the absolute value Dx is above ($y < |\mathrm{Dx}|$), the behaviour of the factor of relevance ($X$) is considered to be anomalous. The expression $p = \pm 100\ (|\mathrm{Dx}| - y)/y$, in Eq. (4), specifies the parameter variation, $p$ in percentage from the state that is devoid of disturbance. The $y$ value must be depended on the earthquake magnitude as $y$ increases with earthquake magnitude. For instance, in big seismic events with magnitude above 7.0, $y$ can be chosen above 2.0. Hence, the $y$ values used in this work were 1.8 and 2.0 for Honshu (Japan) and Vanuatu earthquakes, respectively. The existing changes in the ionospheric parameters are predicated on duration of the local time. In view of this, the TEC, $M$ and IQR computed values were assessed throughout the total time interval of concern for individual period of 60 min in Local Time.

## Observations of the case studies

As earlier emphasised in the introductory remark, to avoid uncertainty associated with the analysis of earthquake anomaly detection, studies past episodes and devices as well as case studies are often established. Seismo-ionospheric perturbations before the earthquakes days have disclosed that 73% of earthquakes that have magnitude 5.0, and 100% of seismic activity characterised by magnitude 6.0 have been established already (Pulinets et al. 2003). Employing the seismic databases obtained from the sites: http://earthquake.usgs.gov, http://www.igs.org/network and www.gfz-potsdam, and regarding the existence of GPS and DEMETER data, two earthquakes occurring at Vanuatu and Honshu (Japan) on March 25, 2007, were selected for this study. The TEC data were accessed using the RINEX (Receiver Independent Exchange) file format through the Gopi software. Two stations within the earthquake preparation zones were selected having station code PTVL and USUDA for Vanuatu and Honshu, respectively. The statistical data concerning the characteristic features of these earthquakes are presented in Table 1, while Table 2 provides the list of earthquakes and their detected anomalies as well as other parameters that helped in the analysis.

## Results and discussion

### Vanuatu seismic activity

In Vanuatu islands, a major earthquake happened on 0.40 Universal Time Coordinate (UTC) on March 25, 2007, with a magnitude $M_{\mathrm{W}} = 7.1$ (see Table 1). Figure 1a shows the DTEC values assessed by Eq. (4) beginning on February 23 through April 4, 2007, via GPS ground locations near the epicentres with station code PTVL. From pictorial scrutiny

**Table 1** Earthquakes investigated and their details, in this study (*Source*: http://earthquake.usgs.gov/)

| Area | Date | Time (UTC) | Geographic lat./long. | Magnitude ($M_{\mathrm{w}}$) | Focal depth km |
|---|---|---|---|---|---|
| Vanuatu | March 25, 2007 | 00:40:00 | 20.66S, 169.43E | 7.1 | 35 |
| Honshu (Japan) | March 25, 2007 | 00:41:00 | 37.28 N, 136.60E | 6.7 | 5 |

**Table 2** List of the earthquakes and detected anomalies

| Earthquake identity | | | TEC | | | Demeter | | | | Geomagnetic indices | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Date | Time | Day | Time | Value | Day | Value | Sensor | Parameter | Time | Kp | Dst |
| Vanuatu | March 25, 2007 | 00:40 | −29 | 05:00 | 2.57 | −25 | 4.33 | IAP | Total ion density | 22:30 | −27 | −25 |
| | | | −28 | 04:00 | 2.84 | −18 | 2.94 | IAP | Total ion density | 22:30 | −26 | −24 |
| | | | −28 | 05:00 | 3.14 | −17 | 4.33 | ISL | Electron temperature | 22:30 | −26 | −19 |
| | | | −25 | 04:00 | 2.6 | | | | | | −25 | −18 |
| | | | −25 | 05:00 | 2.86 | | | | | | −24 | −17 |
| | | | −21 | 04:00 | 2.9 | | | | | | −19 | −12 |
| | | | −21 | 05:00 | 3.19 | | | | | | −18 | −2 |
| | | | −19 | 06:00 | 2.5 | | | | | | −13 | −1 |
| | | | −18 | 04:00 | 2.79 | | | | | | −12 | 0 |
| | | | −16 | 04:00 | 3.25 | | | | | | −11 | 7 |
| | | | −16 | 06:00 | 2.51 | | | | | | −9 | 8 |
| | | | −14 | 00:00 | 8.73 | | | | | | −1 | 9 |
| | | | −14 | 01:00 | 11.16 | | | | | | 0 | 10 |
| | | | −14 | 02:00 | 12.54 | | | | | | 2 | |
| | | | −14 | 03:00 | 12.86 | | | | | | 7 | |
| | | | −14 | 04:00 | 12.29 | | | | | | 8 | |
| | | | −14 | 05:00 | 12.14 | | | | | | | |
| | | | −14 | 06:00 | 10.73 | | | | | | | |
| | | | −14 | 07:00 | 8.62 | | | | | | | |
| | | | −14 | 08:00 | 5.69 | | | | | | | |
| | | | −14 | 09:00 | 4.4 | | | | | | | |
| | | | −14 | 10:00 | 2.79 | | | | | | | |
| | | | −14 | 11:00 | 2.63 | | | | | | | |
| | | | | | −14 | | | | | | | |
| | | | −14 | 21:00 | 4.76 | | | | | | | |
| | | | −14 | 22:00 | 5.76 | | | | | | | |
| | | | −14 | 23:00 | 6.72 | | | | | | | |
| | | | −14 | 00:00 | 8.73 | | | | | | | |
| | | | 8 | 23:00 | 2.6 | | | | | | | |
| | | | 9 | 03:00 | 2.52 | | | | | | | |
| | | | 9 | 04:00 | 2.8 | | | | | | | |
| Honshu (Japan) | March 25, 2007 | 00:41 | −24 | 04:00 | 2.87 | −28 | 7.77 | ISL | Electron density | 22:30 | −27 | −25 |
| | | | −21 | 03:00 | 3.19 | −28 | 5.03 | IAP | Total ion density | 22:30 | −26 | −24 |
| | | | −21 | 04:00 | 3.01 | −26 | 2.41 | ISL | Electron temperature | 22:30 | −26 | −19 |
| | | | −21 | 05:00 | 4.06 | −25 | 3.38 | ISL | Electron density | 22:30 | −25 | −18 |
| | | | −20 | 05:00 | 3.18 | −25 | 3.45 | IAP | Total ion density | 22:30 | −24 | −17 |
| | | | −15 | 03:00 | 3.07 | −22 | 8.06 | ISL | Electron density | 10:30 | −19 | −12 |
| | | | −15 | 04:00 | 2.86 | −22 | 4.78 | IAP | Total ion density | 10:30 | −18 | −2 |
| | | | −15 | 05:00 | 2.89 | −20 | 4.01 | ISL | Electron density | 10:30 | −13 | −1 |
| | | | −11 | 04:00 | 3.13 | −20 | 2.64 | IAP | Total ion density | 22:30 | −12 | 0 |
| | | | −11 | 05:00 | 2.83 | −14 | 3.24 | ISL | Electron density | 22:30 | −11 | 7 |
| | | | −9 | 03:00 | 2.72 | −9 | 4.47 | ISL | Electron density | 22:30 | −9 | 8 |
| | | | −9 | 04:00 | 2.73 | −9 | 3.04 | IAP | Total ion density | 22:30 | −1 | 9 |
| | | | −8 | 03:00 | 2.59 | −6 | 3.58 | IAP | Total ion density | 10:30 | 0 | 10 |
| | | | −8 | 04:00 | 3.1 | −6 | 6.76 | ISL | Electron density | 10:30 | 2 | |
| | | | −6 | 04:00 | 3.47 | −4 | 3.49 | ISL | Electron density | 10:30 | 7 | |
| | | | −4 | 04:00 | 3.52 | | | | | | 8 | |
| | | | −3 | 03:00 | 2.93 | | | | | | | |
| | | | −3 | 04:00 | 2.84 | | | | | | | |
| | | | −1 | 02:00 | 2.65 | | | | | | | |
| | | | 9 | 03:00 | 3.83 | | | | | | | |

**Table 2** (continued)

Day is relative to the earthquake day. Value calculated by: $(x - M)/\mathrm{IQR}$ : $x$ , $M$ and IQR are parameter value, median of parameter values in defined period and inter-quartile range of parameter values in defined period, respectively. Values calculated in terms of the upper and lower bounds defined for each earthquake as follow: Vanuatu (DEMETER: $M \pm 2.0 \cdot \mathrm{IQR}$); and Honshu (DEMETER: $M \pm 1.8 \cdot \mathrm{IQR}$)

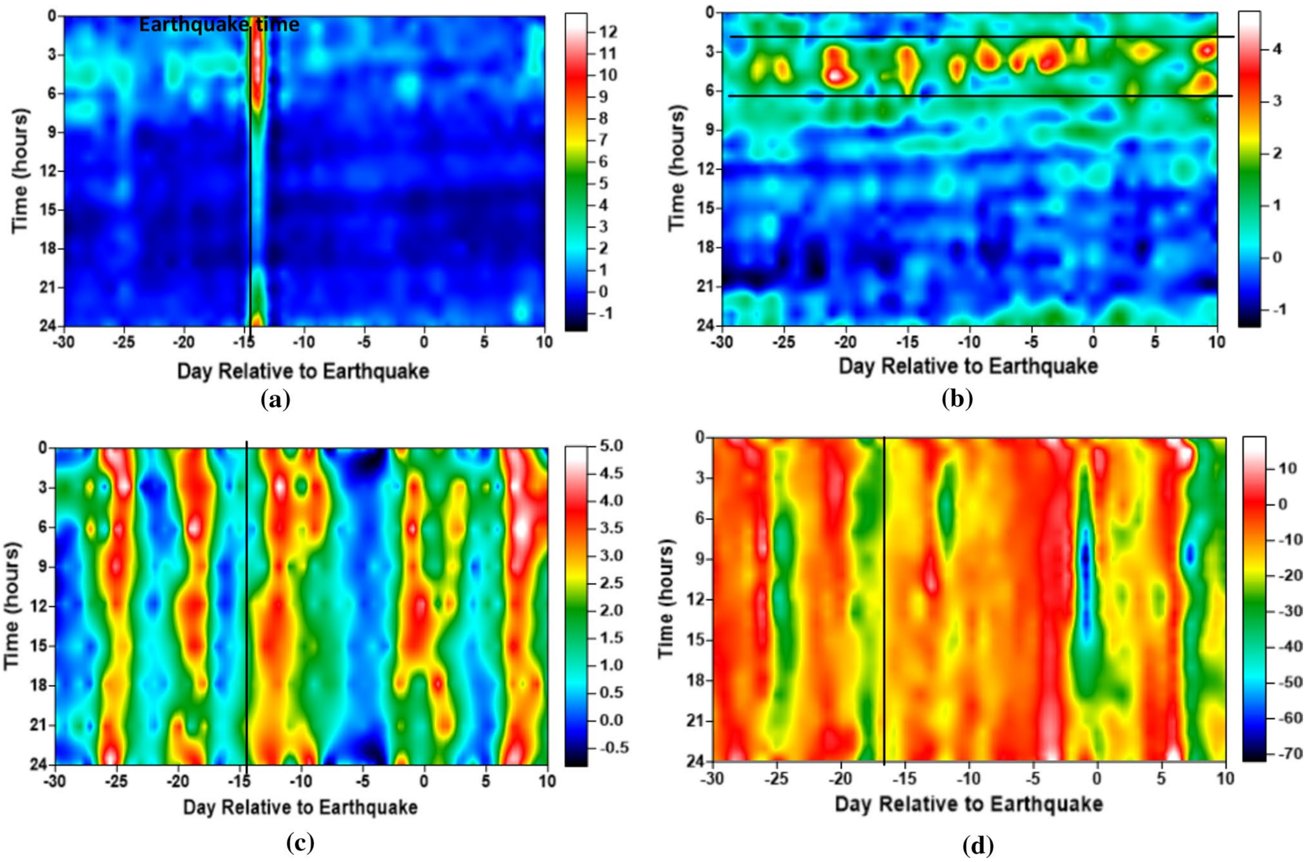


**Fig. 1** Results of analysis for the Vanuatu and Honshu (Japan) earthquakes (March 25, 2007) from February 23 to April 4, 2007. The $x$-axis represents the day relative to the earthquake day. The $y$-axis represents the time UTC **a** DTEC variations for Vanuatu. **b** DTEC variations for Honshu (Japan). **c** Variations of Kp geomagnetic index. **d** Variations of $D$st geomagnetic index

of DTEC anomalies, perturbations were observed before the earthquake date, predominantly the variations of − 14 days relative event (earthquake day). However, to separate earthquake distortions associated with magnetic and solar disorders, changes of Dst in addition to variations in Kp indices within the same time domain were integrated. Fig. 1c, d illustrates, correspondingly, the associated changes in Kp and Dst indices within similar time window. The TEC illustrated ionospheric variations on the following days − 29, − 28, − 25, − 21, − 19, − 18 and − 16 about the same time each day (4:00–6:00 h). On − 14 days (exactly two weeks before the earthquake), there were significant perturbations all through that day. Relating these abnormalities with geomagnetic irregularities within the same time, the Kp had insignificant activity on that day while the Dst index displayed no activity on the said day. The black line drawn on Fig. 1a, c, d clearly shows this. Geomagnetic activities were seen on − 25, − 19 and − 18 days preceding the event. Hence, the observed perturbations could not be entirely seismogenic. They were two cases of post-seismic perturbations (8th and 9th days after the seismic event). These occurred on active geomagnetic days and hence could not be seismogenic.

The IAP and ISL sensors of the DEMETER from trajectories nearby the epicentre were likewise investigated within the same time frame. Assessing the total ion density

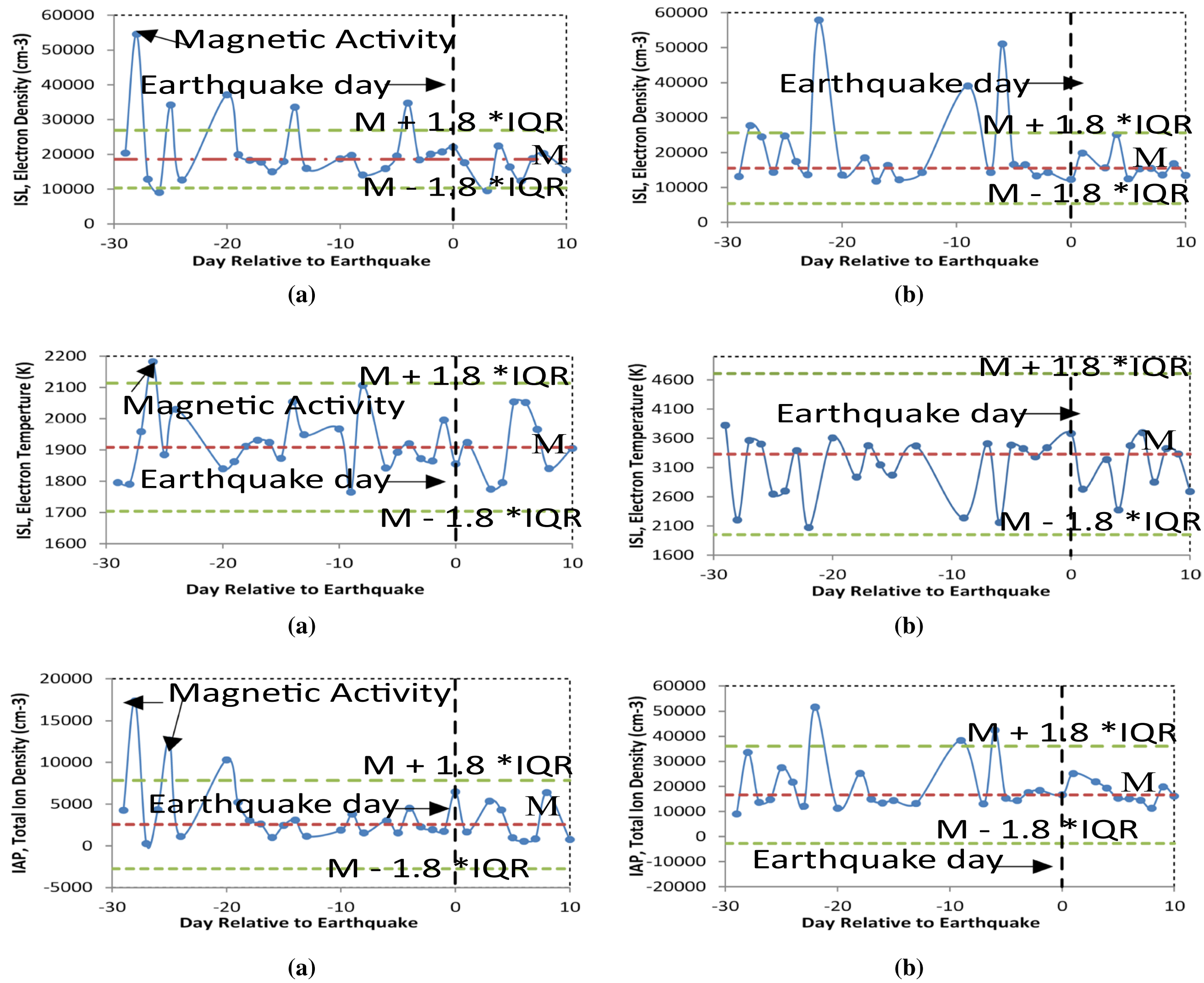


**Fig. 2** Results of DEMETER data analysis for the Honshu (Japan) earthquake of March 25, 2007. The earthquake day is represented as vertical dotted line. The green horizontal lines indicate the upper and lower bounds ($M \pm 1.8 \star$ IQR). The red horizontal line indicates the median value ($M$). The $x$-axis represents the day relative to the earthquake day. The y-axis represents (i) electron density derived by the measurements of the ISL experiment (ii) electron temperature derived from the measurements of the ISL experiment and (iii) total ion density derived from the measurements of the IAP experiment during **a** night and **b** morning

within this period, − 25 and − 18 gave abnormal ionospheric ion densities. These variations were observed during the night-time measurements of the DEMETER. Screening for geomagnetic activities revealed that these perturbations occurred when both Kp and Dst indices were not quiet; hence, the perturbations were not actually seismogenic. Nevertheless, the measured electron temperature on − 17 days occurred in quiet geomagnetic period, suggesting it to be seismogenic.

## Honshu (Japan)

At about 0:41 h, on March 25, 2007, a 6.7-magnitude earthquake occurred in Honshu, Japan. Both GPS and DEMETER data were investigated 30 days before and 10 days after the said earthquake to assess the state of the ionosphere prior to this seismic event. Figure 1b shows the DTEC values assessed by Eq. (4) beginning on February 23, through April 4, 2007 via GPS ground locations nearby the epicentre with station code USUD. The TEC

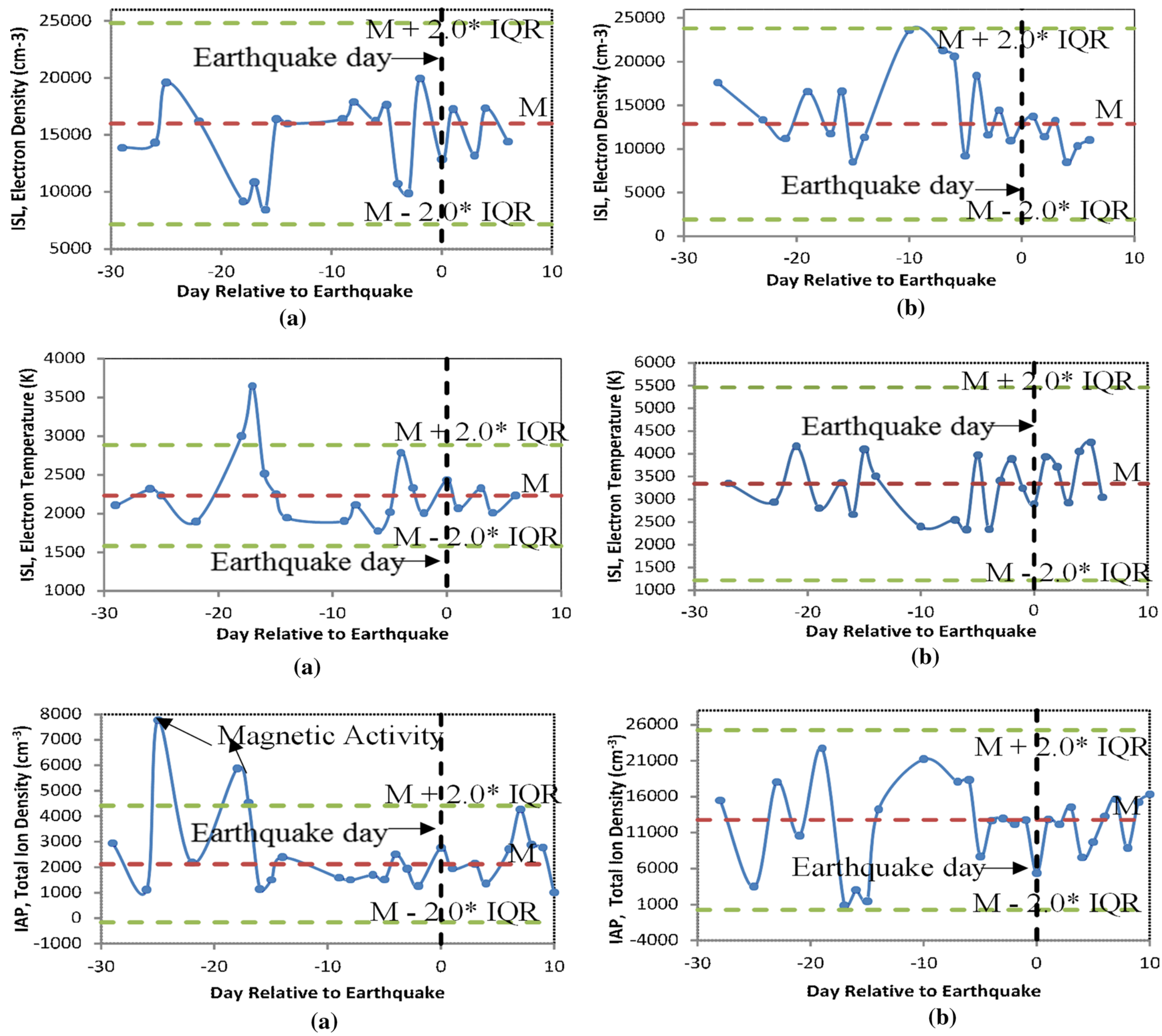


**Fig. 3** DEMETER data analysis for the Vanuatu earthquake of March 25, 2007. The earthquake day is represented as vertical dotted line. The green horizontal lines indicate the upper and lower bounds ($M \pm 2.0 \star$ IQR). The red horizontal line indicates the median value ($M$). The x-axis represents the day relative to the earthquake day. The y-axis represents (i) electron density derived from the measurements of the ISL experiment (ii) electron temperature derived from the measurements of the ISL experiment and (iii) total ion density derived from the measurements of the IAP experiment during **a** night and **b** morning

measurements showed strong variations within three weeks to the earthquake. From Fig. 1b perturbations are seen on −21, −15, −8, −6 and −3 days between the hours of 3 and 5 as displayed in the said figure by the two horizontal black lines. However, since the state of the ionosphere is not controlled only by large interior earth processes, the observed perturbations had to be screened for geomagnetic induced variations. Consequently, 80% of the observed irregularities happened in quiet geomagnetic periods. Consequently, it is pertinent to associate these ionospheric perturbations to the seismic event (Figs. 2, 3).

The ISL and IAP experiments of the DEMETER were also employed to assess the state of the ionosphere within the same period regarding this earthquake. Both sensors recorded variations outside of its upper and lower bounds in the three investigated parameters of electron temperature, electron density, and total ion density within the study period. All detected anomalies were pre-seismic activities of which 20% were geomagnetically induced.

Correlating both the GPS and DEMETER data, perturbations simultaneously occurred on some days (− 20, − 9, − 6 and − 4 days) before the earthquake which incidentally displayed no activity on both Kp and Dst indices. These strongly indicated that these variations were seismogenic—an indicator to the large earth interior process that was on its way. Although good results have been realised, from the chosen methodology, which employs ISL and IAP, other DEMETER experiments like ICE, IDP and IMSC can also be used to constrain the validity and fidelity of present result.

## Conclusion

Ionospheric plasma parameters assessed from the analyses of the GPS and DEMETER data revealed that seismo-induced perturbations occurred in the region of two earthquakes of March 25, 2007. The result leads to the conclusion that the seismo-induced variations were clearly obvious for some days before each seismic event. The Vanuatu earthquake presented very strong TEC variations 14 days before it during quiet geomagnetic period. The Honshu (Japan) earthquake exposed very strong instabilities few days to the event simultaneously on both DEMETER and GPS data, when Kp and Dst displayed no activity. These ionospheric perturbations in quiet geomagnetic period could give indications of the impending seismic hazard. A careful monitoring of the ionosphere can help assess for seismo-induced perturbations.

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**Authors' Contribution** AEA and JII conceived the study, designed the framework and searched for DEMETER data. AME used appropriate software programs to interpret the data while NJG puts together the write up using the processed data and performed grammar checks as well as work on the references.

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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