RESEARCH ARTICLE - SOLID EARTH SCIENCES

Ionospheric perturbations: a case study of 2007 five major earthquakes using DEMETER data

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Abstract

Using the Plasma analyzer (IAP) and Langmuir Probe (ISL) experiments of the Detection of Electromagnetic Emissions Transmitted from Earthquake Regions (DEMETER) lithospheric–atmospheric–ionospheric coupling has been observed before, during and after five major earthquakes with magnitudes greater than 6.5. The aim of this study is to use ionospheric parameters to identify the ionospheric perturbations associated with the five earthquake regions screened. All the three investigated ionospheric parameters of electron density, electron temperature and total ion density recorded perturbations within the investigative period. A total of 36 anomalies were obtained with 18 each for nighttime and daytime readings. The observed anomalies being screened for false alarm using the geomagnetic indices of Kernnifzer digit (kp) and disturbance storm time (Dst.) revealed 27.8% as geomagnetically induced perturbations. Thus, 72.2% of the studied anomalies transpired in quiet geomagnetic conditions, which is linked to seismic events.

Keywords Earthquake · DEMETER · Perturbations · Seismogenic perturbation · Geomagnetic perturbation

Introduction

The anguishes caused by earthquakes have persistently driven researchers worldwide to carry out broad-based researches on various observable facts linking to this devastating event with the exclusive aim of predicting their occurrences. Thoughtful knowledge of earthquake corollaries and ways of extenuating them has constantly dominated scientific discussions at various levels and social fora and this can go nonstop until the planned intention is achieved.

Earthquakes of various types and magnitudes take place almost every year in some earthquake-prone areas across the globe. In a nutshell, earthquakes refer to any seismic event emanating from either natural or human activities, which spawn seismic waves that propagate through the earth's interior. Thus, apart from earthquakes from natural causes, whose occurrences are sometimes more cataclysmic, earthquakes can also be provoked by human activities such as mining (Francesco and Bizzarri 2014; Bommer et al. 2015), groundwater over exploitation (Gupta 1983; Klose 2013), oil exploration and exploitation activities (Davies et al. 2013; McGarr 2014; Thomas et al. 2020), and dam construction (Verdugo and Gonzalez 2015). However, earthquakes emanating from human actions are generally of low magnitudes (tremors/microseisms). In all cases, the naturally induced earthquakes have huge amount of elastic strain energy released during their occurrence and their effects have sustainably gingered up man's dire need to tease out the reliable precursors for them. The prominently asked question is "what transpired in the weeks, days and even hours before this scary event occurred? Is there any possible pointer to such an event?" It is acknowledged from research findings that all seismic electromagnetic anomalies are indicative of the processes, which started days afore the main event and persisted few days after it (Akhoondzadeh et al. 2010; Ibanga et al. 2017). Earthquake on its own barely kills/destroys people or animals, but the secondary events prompted by it, such as collapse of buildings, fires, tsunamis (seismic sea waves) and volcanoes, are in fact the chief causes of human debacle.

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The physical processes governing earthquakes are very complicated. It is neither systematic nor direct. The complexities involved make prediction of earthquake to be very uncertain. Thus, dependable techniques of studying, monitoring and thoughtful understanding of the fundamental chemical and physical processes precede them must be discerned. Prior to an earthquake activity, a gigantic quantity of energy is usually released due to crustal motion, and at the instant of the shock, a break down occurs between the source of the energy and the environment. Research findings have opined that these observable changes before, during and after such events do have varying physical and chemical effects on the lithosphere, atmosphere and ionosphere (Hayakawa and Molchanov 2002; Rapoport et al. 2004; Rozhnoi et al. 2009; Chmyrev et al. 2013; Thomas 2021), thus making their detection possible. Consequently, noticeably perturbations in threshold status of lithospheric, atmospheric and ionospheric parameters can serve as indicators (precursor) of earthquakes. If these ionospheric prominent perturbations are systematic and real, then they can be regarded as short-term precursor, transpiring before, after or between the seismic events.

All precursors are not predictable in all seismic events; therefore, a single precursor cannot be employed alone to forecast earthquakes; however, an integrated approach deploying different precursors from diverse experiments such as the one used in this study is the most preferred. On the basis of this premise, this work is therefore aimed at deploying ionosphere parameters to identify the ionospheric perturbations linked to the five earthquake regions investigated.

Datasets

DEMETER data

DEMETER is a microsatellite launched by the French Space Agency known as *Centre National D'etudes Spatiales* (CNES). This microsatellite has been functioning between 2004 and 2010. It operated on a polar and circular sun-synchronous orbit with an altitude of 710,000 m (reduced to 660,000 m in 2005). Amongst the six experiments of the scientific payload include the Plasma analyzer (IAP) instrument, which was cautiously designed to record the parameters of the thermal population, which are the densities of the main ionospheric ions: hydrogen (H+), helium (He+) and oxygen (O+) (within a range of 10^2–5.10^5 ions/cm^3); the temperatures, which ranged from 500 to 5000 K and the ion flow velocity in the earth's frame of reference (Berthelier et al. 2006). With the Langmuir (ISL) probe sensor, the in situ measurement of the electron density and temperature was made (Lebreton et al. 2006). Owing to technical/scientific reasons, data were only recorded at invariant latitudes below 65°. Although DEMETER satellite mission stopped on December 9, 2010, its data were archived at Centre de Données de la Physique des Plasmas (CDPP) and they can be accessed using the web server (http://demeter.cnrs-orleans.fr//). The data were prepared/organized and plotted in half orbits. The CDPP gave enormously potential array of data to examine perturbations in electromagnetic emissions, generation of plasma inhomogeneities and other ionospheric phenomena coupled with seismic events. The highly sensitive nature of these data gave credence to its reliability/validity. The present study deployed data from the ISL and IAP sensors, which were in the burst mode according to Parrot (2012) and Ibanga et al. 2017).

Geomagnetic datasets

Regional and considerably large-scale variations in the atmospheric electricity over seismically active zones before the seismic shocks were transformed to the ionosphere through a large-scale electric field. Consequent upon the penetration of this electric field into the ionosphere, anomalous electron concentrations were according to Dobrovolsky et al. (1979) observed when the affected region had an area with a diameter greater than 200 km^2. Conversely, the observed disparities in the ionospheric parameters were not just provoked only by earthquakes but were also considered to be due the abundant potential of ionospheric distresses originated originate from other sources such as acoustic gravity waves, solar activity, plasma dynamics, traveling ionospheric disturbances and large meteorological phenomena. As a result, the observed parameters may display variations in the dearth of seismic event. Therefore, it is hard to detach pre-seismic ionospheric phenomena from the ionospheric variations occasioned by solar-terrestrial activities (Ondoh 2008). Accordingly, to discriminate the seismo-ionospheric perturbations from geomagnetic instabilities, the geomagnetic indices of Dst and Kp were checked (Bascıftcı 2021; Bulbul and Basciftci 2021; Basciftci 2022; Basciftci and Bulbul 2022). The Kp index screened the planetary activity on a universal scale whereas the Dst index registered the equatorial ring current variations (Mayaud 1980). The ionospheric control of the geomagnetic storm has a worldwide effect observed in all over the world while the seismogenic influence was observed primarily in places within the radius (R) of the earthquake preparation zone of magnitude m given by the value ($R = 10^{0.43m}$) according to Dobrovolsky et al. (1979).

Methodology

The five earthquakes used in this study (Table 1) (USGS 2015) had relevant information including time of occurrence, geographic location and magnitude of event, and

orbits closest to the epicenter (at a resolution of 20° for longitude and 10° for latitude) were selected 30 days prior and 10 days after the earthquake. This duration was well selected to give sufficient time in monitoring of the ionospheric plasma parameter from its natural to perturbed state, enhancing separation of seismic anomalies from the background of natural variations, expecting the former to appear at the end of the period. Different time windows ranging from five days to two months have been used to monitor the ionosphere but principally, reports on seismo-electromagnetic variations are observed three weeks or less to the earthquake day (Píša et al. 2011; Parrot 2012; Thomas et al. 2021, 2022). The total ion density (Oxygen, Hydrogen and Helium ions from the IAP Sensor), Electron temperature and Electron density (from the ISL Sensor) were obtained by downloading data files from the DEMETER website. Data from each orbit were curbed in two modes (survey and burst) but only the burst mode data were employed in this study. The median and the inter-quartile range of the data were used to obtain their upper and lower limits in order to discriminate seismic variances from the background of regular variations. A reference value k was selected proportional to earthquake magnitude in each event (with values ranging from 1.8 to 2.2) (Ibanga et al. 2017; Akpan et al. 2019). Any variations outside these bounds were anomalous. These involved computation of upper and lower boundaries, median value and inter-quartile range using Eqs. (1)–(3) as follows:

$$x_{high} = M + k \cdot IQR \tag{1}$$

$$x_{low} = M - k \cdot IQR \tag{2}$$

$$x_{low} < x < x_{high} \Rightarrow -k < \frac{x - M}{IQR} < k; \, Dx = \frac{x - M}{IQR}, \tag{3}$$

where x, x_{high}, x_{low} M, IQR and Dx are parameter values, upper bound, lower bound, median of the data, inter-quartile range and differential of x, respectively. From Eq. (3), if the absolute value of Dx is greater than k, (i.e., |Dx|> k), then the behavior of x is considered to be anomalous. k values must be selected to be proportional to earthquake magnitude, and therefore, for large events with Magnitude > 7.0, values greater than 2.0 were used.

Results obtained from analyses of DEMETER datasets

The temporal fluctuations in the form of ionospheric plasma parameters—electron density (cm⁻³), electron temperature (K) and total ion density (cm⁻³) obtained from ISL and IAP experiments performed on board DEMETER satellite have been investigated. The experimental data, meant for deciphering the influence of seismo-electromagnetic signals on plasma parameters, were acquired when DEMETER satellite passed orbits closest to the epicenter of the various earthquakes 30 days before and 10 days after each event (Akpan et al. 2019). Six different plots were generated from each zipped data set that was acquired at both day and night times. Thus, for the studied five earthquakes, a total of 27 plots were generated and studied appropriately. These data were downloaded in compressed zip files, and IDL virtual machine software was used to unzip them. All computations and graphical analyses were performed using Microsoft Excel. Using geographic coordinates of the epicenters of the various earthquakes available in the data, anomalous behaviors during the 30 days monitoring period were identified from regular variations.

Figures 1, 2, 3, 4 and 5 demonstrate variations of the dissimilar parameters obtained in the study. In all the panels, the upright dotted line revealed the day of earthquake while the ordinate of each panel revealed the relative days to earthquake and after the earthquake day. Median, upper and lower bounds can be, respectively, identified with red and green horizontal lines. The y-axis represents various

Table 1 The analyzed earthquake locations and their associated Parameters (USGS 2015)

| S/N	Area	Date	Time (UTC)	Geographic *latitude*, longitude	Magnitude Mw	Focal depth (km)
1	Molucca Sea, Indonesia	01/21/07	11:27	*1.22* 126:39	7.5	22.0
2	Central Peru	08/15/07	23:40	*− 13.35* − 76.51	8.0	39.0
3	Mariana Islands region, USA	09/28/07	13:38	*22:01* 142.39	7.5	260.0
4	Martinique region, France	11/29/07	19:00	*14.94* − 61.24	7.4	146.2
5	Off East Coast of the North Island, New Zealand	12/20/07	07:55	*− 38.84* 177.93	6.6	35.6
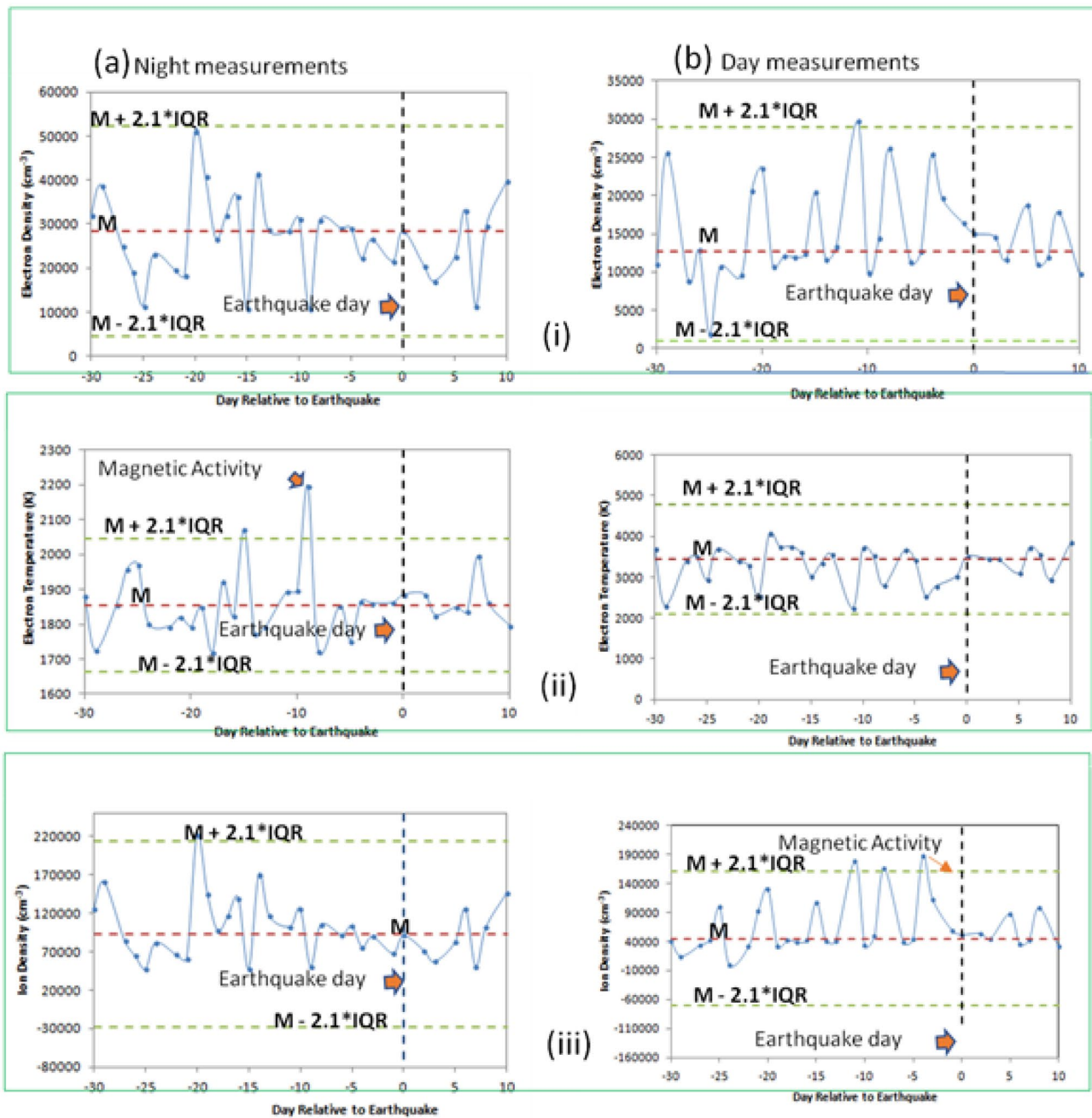
Fig. 1 Results of morning and afternoon DEMETER data analysis for Molucca Sea Earthquake of 01/21/07 for electron density (i), electron temperature (ii) and total ion density (iii)

parameters such as (i) electron temperature derived from the measurements of the ISL (ii) experiment electron density derived from the measurements of the ISL experiment, (iii) total ion density obtained from determinations of the IAP experiment during (a) night and (b) day. Figures 6 and 7, respectively, show the results of perturbation/disturbance storm time (dst) and kp indices for the geomagnetic variations distributions in the five earthquakes studied analyzed.

Discussion of results

Molucca Sea earthquake of 01/21/07

DEMETER orbits within the earthquake preparation zones were downloaded and analyzed for possible seismo-induced variations. The study clearly showed a total of 8 perturbations outside the confidence interval in the three investigated parameters as shown in the DEMETER plots (Fig. 1)

Fig. 2 Results of morning DEMETER data analysis for Central Peru Earthquake of 08/15/07 for electron density (i), electron temperature (ii) and total ion density (iii)
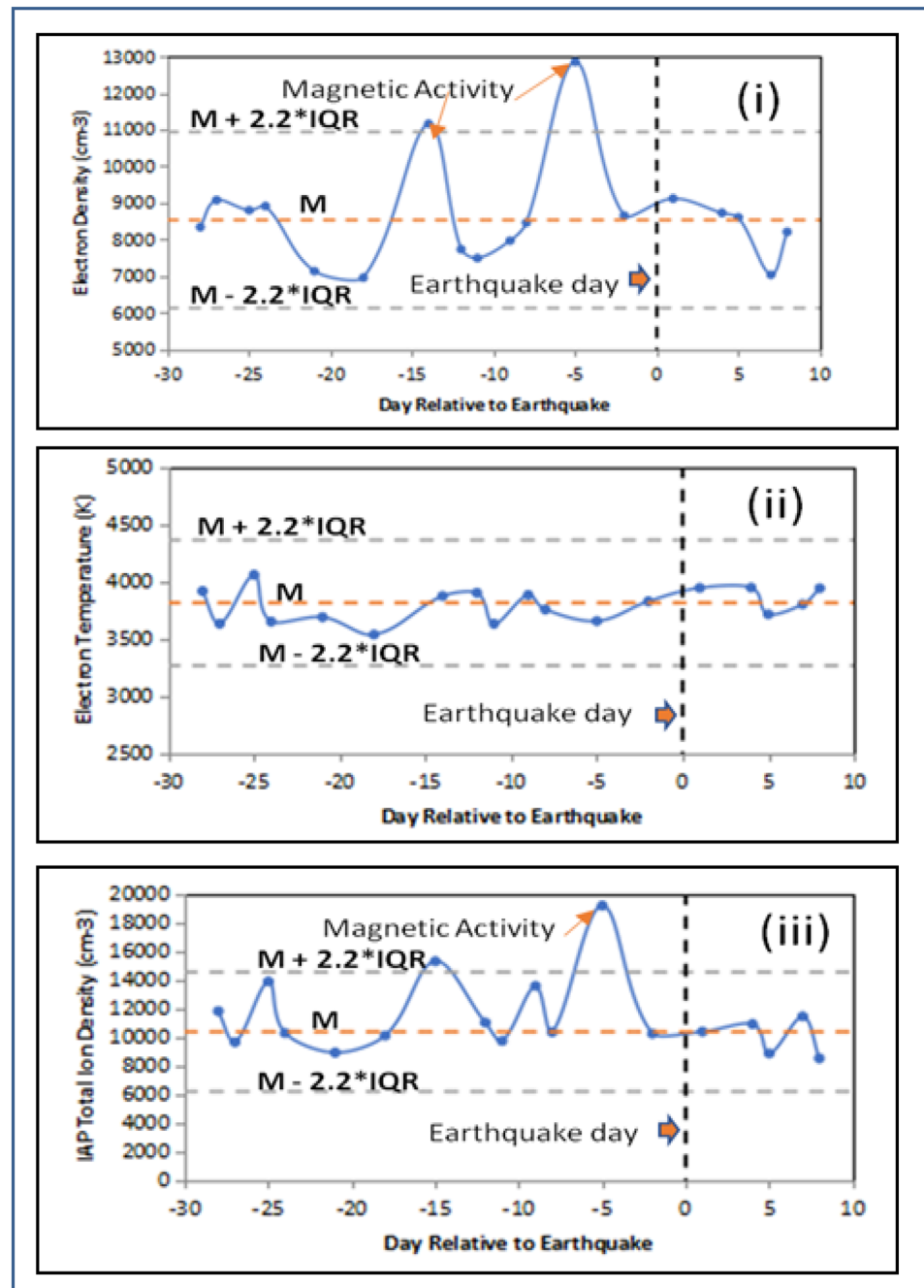
and calculated from Eq. 3. The electron density parameter recorded in the morning was perturbed on −25 days (−1.49 per cm³) and −11 days (1.54 per cm³). However, it was the night reading of electron temperature that recorded unusual values 0f 2.41 K and 3.78 K on −15 days and −9 days, respectively. The IAP experiment displayed perturbations in both night and morning half orbits measurements (Fig. 1a(iii)). From the night orbits measurements, −20 days was perturbed with a value of 1.87 per cm³ while the morning readings recorded three perturbations on −12 days, −9 days and −5 days having anomalous values of 1.93 per

cm³, 1.74 per cm³ and 2.06 per cm³, respectively. By crosschecking for geomagnetic induced perturbations, the Dst (Fig. 6a) was generally quiet almost throughout the investigative period except at the onset but the kp (7a) was active −5 days. Thus, the observed variations (25 %), which were seen 5 days before the earthquake day were geomagnetically induced while the remaining 75% observations were seismically induced according to Ibanga et al. (2017).
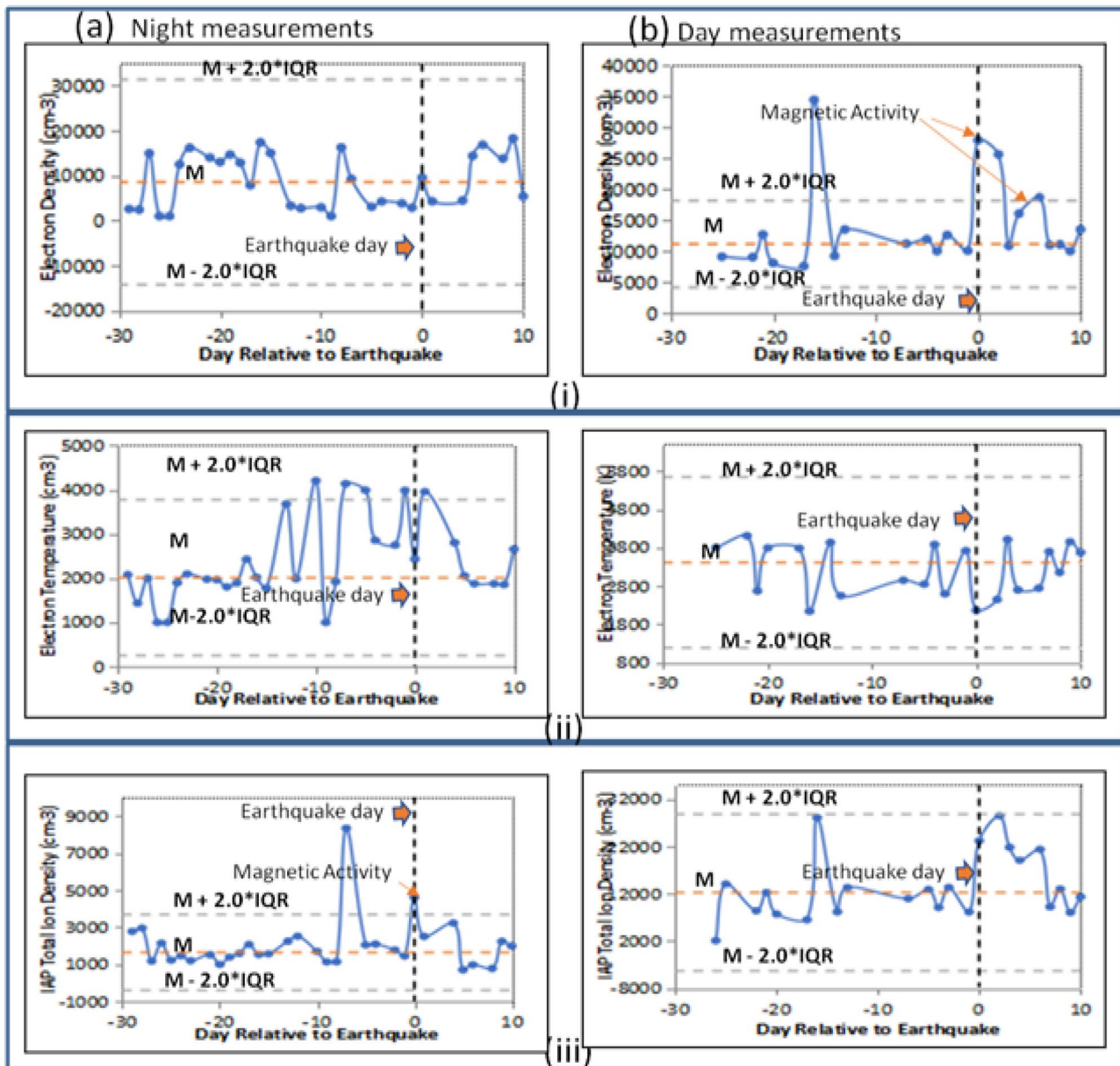
Fig. 3 Results of morning and afternoon DEMETER data analysis for Mariana Islands Region, USA. Earthquake of 09/28/07 for electron density (i), electron temperature (ii) and total ion density (iii)

Central Peru earthquake of 08/15/07

The Central Peru earthquake of August 15, 2007, took place at 23: 40 UTC due to faulting along the boundary where the Nazca plates subducts beneath the South American plate with 519 people dead. DEMETER data from ISL and IAP sensors investigated revealed four unusual perturbations from its morning half orbits measurements (Fig. 2). The electron density was perturbed on − 14 and − 5 days with 2.4 per cm³ and 3.95 per cm³, respectively, as its magnitudes, while the total ion density showed

anomalies on − 15 days (2.6 per cm³) and − 5 days (4.65 per cm³). However, investigating for possible geomagnetically induced variations (Figs. 6b and 7b) revealed that 75% of the observed variations transpired in geomagnetically active period (Thomas et al. 2021, 2022). Hence, the observed variations could not be solely linked to the seismic event. It is also worthy of note that the DEMETER satellite only had just morning measurement for this earthquake.
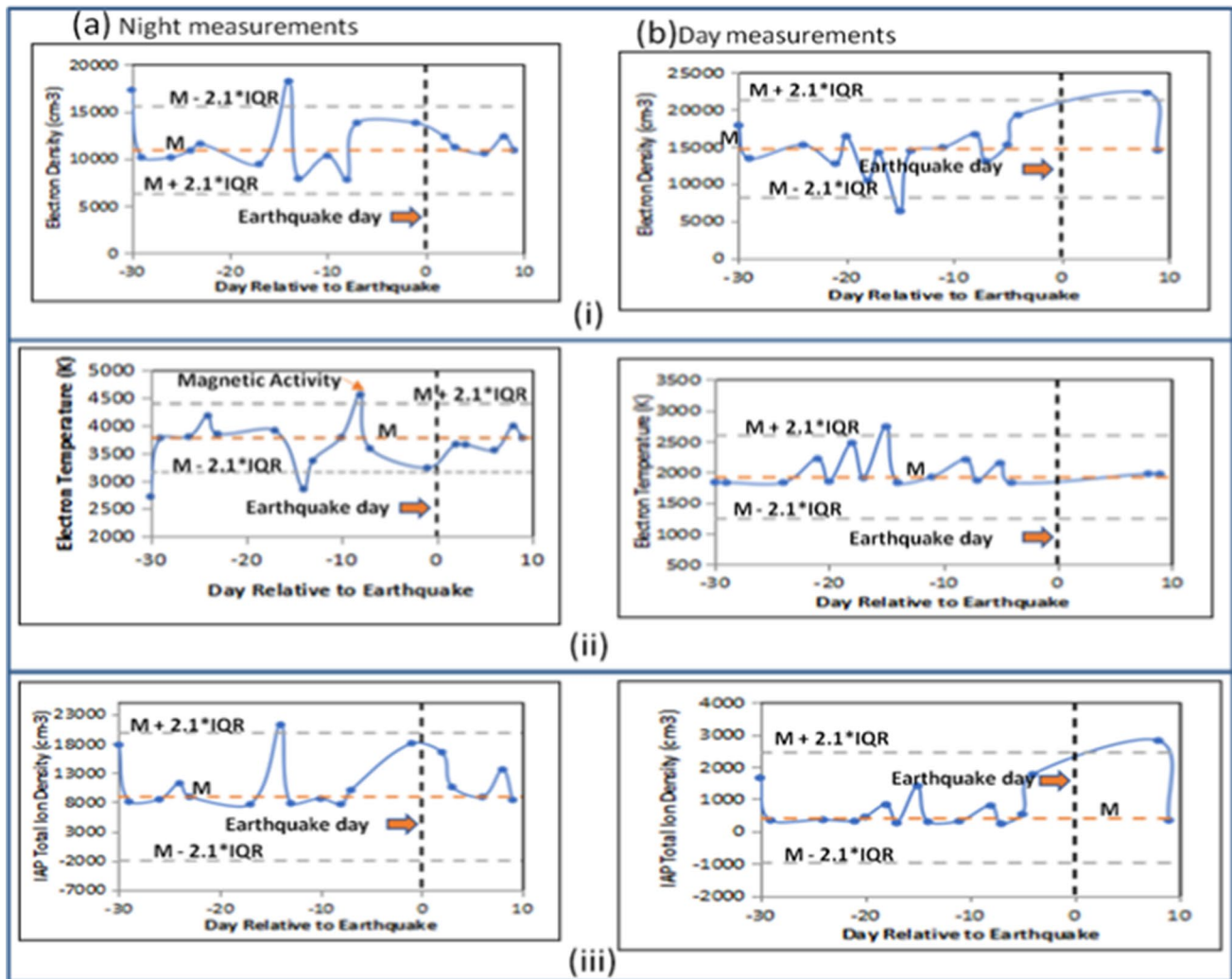
Fig. 4 Results of morning and afternoon DEMETER data analysis for the Martinique Region, France Earthquake of 11/29/07 for electron density (i), electron temperature (ii) and total ion density (iii)

Northern Mariana Islands, USA, earthquake of 09/28/07

At about 13:38 UTC, a M7.5 earthquake struck Mariana Islands region in USA. Figure 3 shows the electron density, electron temperature and total ion density plots obtained from the DEMETER orbits within the seismogenic area during the investigative window. The study clearly identified 11 anomalous points from all three ionospheric parameters. The morning measurement of electron density showed perturbations on − 15, 0, 2, 5 days measuring 6.65 per cm^3, 5.75 per cm^3, 4.34 per cm^3, and 2.6 per cm^3 in that order computed from Eq. (3) while − 10, − 9, − 7, − 1 and 2 days (3.25 K, 3.16 K, 3.12 K, 3.07 K and 2.98 K, respectively) were the perturbations in the night time measurements of electron temperature. Also from IAP experiments, the total ion density presented values of 6.56 per cm^3 and 4.79 per cm^3 on

− 7 and 0 days, respectively, as perturbed days. Both Dst (Fig. 6c) and kp (Fig. 7c) were active from the earthquake day till five days after it. The kp index showed unsettled condition between − 9 and − 7 days afore the seismic event. This agrees with Chmyrev et al. (2013) that the earthquake scenes before and after retain uncharacteristic variations in geomagnetic indices. This research showed that about 36.4% of these variations were from Dst and kp activities. The very high value of 6.65 per cm^3 obtained on 15 day before this event in the electron density occurred when both indices of geomagnetic activities were quiet.

Martinique region, France earthquake of 11/29/07

On November 29, 2007, an intermediate-depth earthquake occurred about 19:00 UTC in the inclined seismic zones that dips to the west beneath the Lesser Antilles Islands
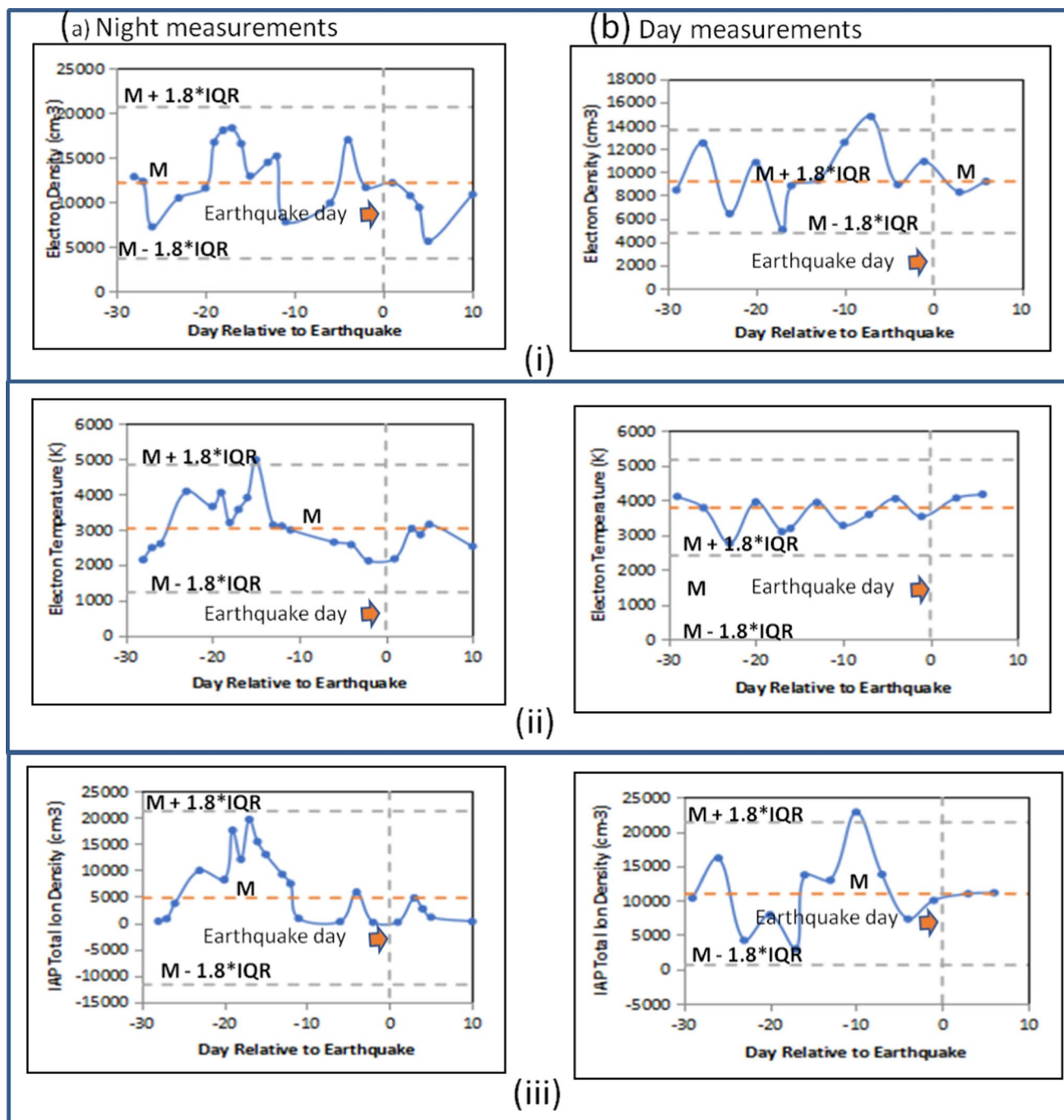
Fig. 5 Results of morning and afternoon DEMETER data analysis for the Off East Coast of the North Island, New Zealand Earthquake of 12/20/07 for electron density (i), electron temperature (ii) and total ion density (iii)

arc within the subducted South American plate responding to pressures caused by plate's slow distortion. Figure 4 gives the DEMETER plots for this seismic event within the study period with 10 points lying outside the confidence boundary. The electron density from nighttime measurement was perturbed on −30 days (2.91 per cm³)

and −15 days (2.68 per cm³) while its daytime observation gave −15 days (−2.45 per cm³) and 8 days (2.42 per cm³) as abnormal days. Three uncharacteristic records were visible in the nighttime readings of the electron temperature on −30, −15 and −8 days having −3.6 K, 2.54 K and 2.66 K correspondingly as their magnitudes. The morning readings of that same electron temperature demonstrated
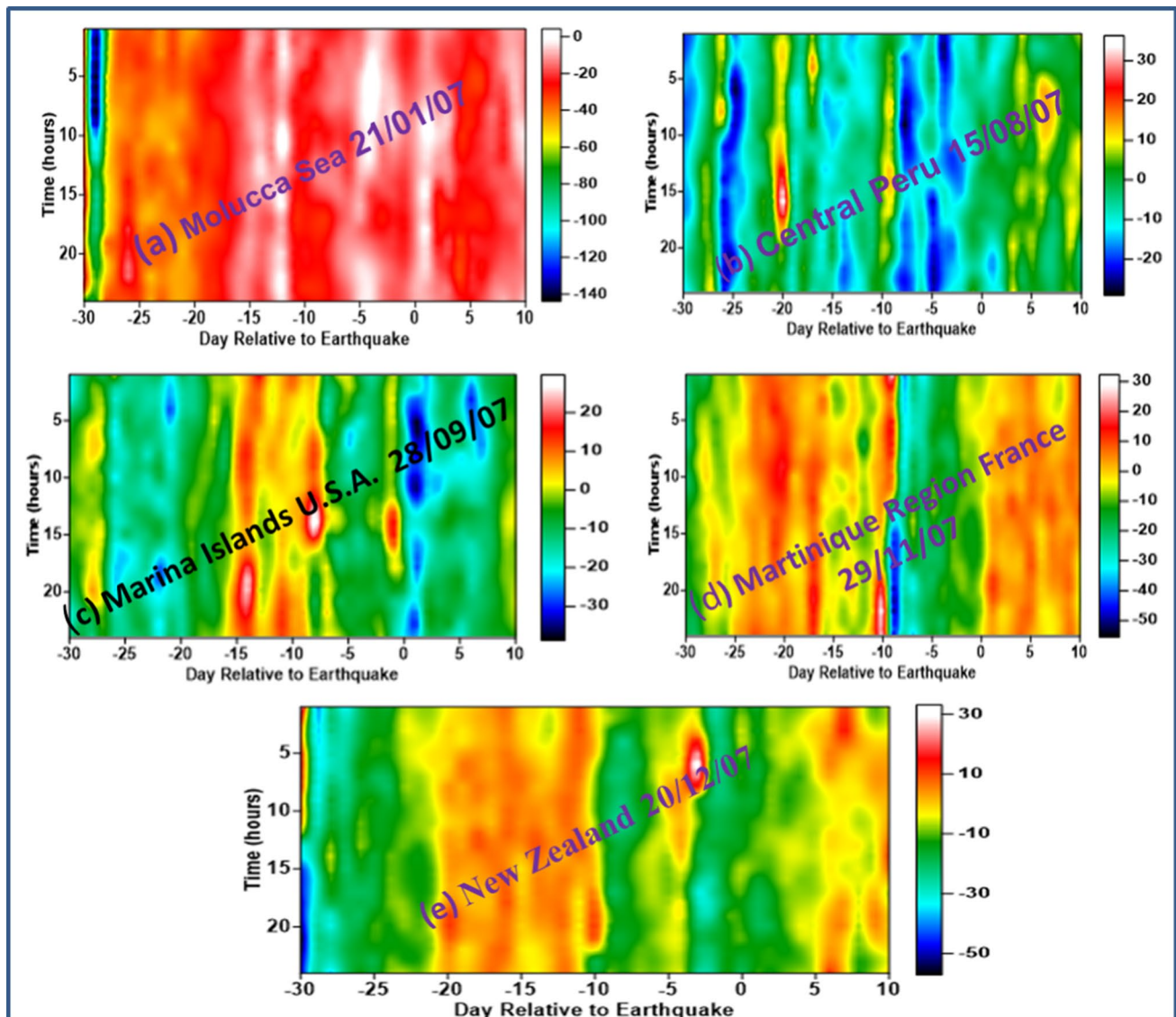
Fig. 6 Results of analysis of variations of Dst geomagnetic indices of the five earthquake locations. The y-axis represents the Time (UTC) while the x-axis represents day relative to earthquake in each case

uncommon value of 2.64 K 18 days afore this seismic event. The investigations also revealed two perturbations from the IAP device where the total ion density measured on − 15 days (2.35 per cm³) nighttime reading and 8 days (2.41per cm³) in daytime reading. Scrutinizing the observed variations for geomagnetically induced perturbations (Figs. 6d and 7d) revealed that apart from the perturbation that occurred—8 days prior to the earthquake all others happened under quiet geomagnetic condition. This is in agreement with (Ibanga et al. 2017). However, Fig. 3d shows a slight unsettlement in the kp condition on − 15 days. Thence, this study shows that about 90% of the perturbations are seismically induced variations (Akpan et al. 2019).

New Zealand earthquake of December 20, 2007

DEMETER orbits closest to the epicenter were selected with a resolution of 20° longitude and 10° latitude using the IAP and ISL experiments. The study revealed a total of three anomalous variations as computed from Eq. (3) and evident in the DEMETER plot (Fig. 5). The electron density measurement obtained from the ISL sensor displayed abnormality 7 days before the seismic event in its morning half orbit with a value of 2.27 per cm³ while a value of 1.94 K was recorded in the electron temperature − 15 days of the earthquake in the same ISL sensor being anomalous. The IAP sensor, which measured the major ionospheric ions, was perturbed 10 days afore the event with a reading of 2.06 per
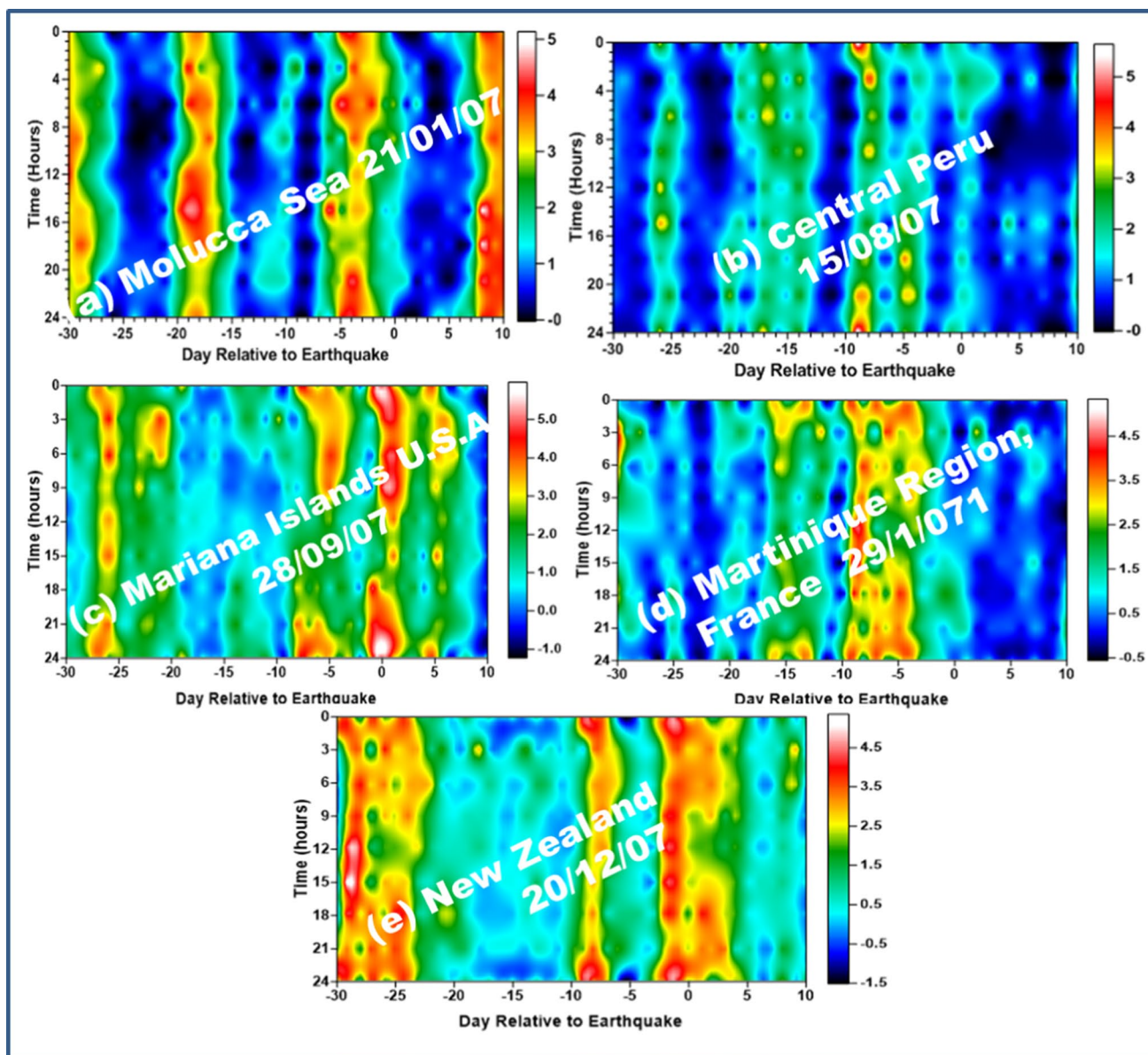
Fig. 7 Results of analysis of variations of kp geomagnetic indices of the five earthquake locations. The y-axis represents the Time (UTC) while the x-axis represents day relative to earthquake

cm^3 in its morning half orbit being unusual. The observed perturbations were subjected to screening for false alarm using the kp and Dst geomagnetic indices (Figs. 6e and 7e) according to Ibanga et al. (2017). These two geomagnetic indices showed no activity on these days; hence, 100% of the observed perturbations were possibly seismogenic in nature.

Conclusion

Ionospheric data investigated at the height of the satellite have been processed for five major earthquakes. In this study, the effectiveness of DEMETER IAP and ISL devices to identify striking anomalies in total ion density, Electron density and temperature parameters have been displayed. A total of 36 anomalies were recorded from all three ionospheric parameters investigated in both nighttime (18) and daytime measurements (18) having both positive and negative signs. Of these anomalous records, 10 (27.8%) of it were geomagnetically induced while 26 (72.2%) were recorded under gamogenetically quiet

period. Also worthy of note is that 70% of the active geomagnetic indices were obtained in the morning half orbits reading. Hence, the identified anomalies under quiet geomagnetic period can be inferred as pre-, co-, post-seismic ionospheric variations. Results from this study are in consonant with previous studies (Akhoondzadeh et al. 2010; Ibanga, et al. 2017; Thomas 2020; Thomas et al. 2021). Characteristically, it is paramount to acknowledge that the ionosphere posses convoluted attribute during quiet geomagnetic circumstance and the inferred parameters at times identified changes in quiet seismic circumstance that can be linked to other uncertain factors. The seismo-ionospheric deviations represented in this work are potentially useful for the short-term prediction. Moreover, it is thoughtful to investigate for more accurate regional model of quiet time for the ionosphere in order to pigeonhole seismic precursors from the background of daily variational perturbations.

Declarations

Conflict of 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.

Human or animal rights This article does not contain studies with human or animal subjects.

References

Akhoondzadeh M, Parrot M, Saradjian MR (2010) Electron and ion density variations before strong earthquakes (M>6.0) using DEMETER and GPS data. Nat Hazards Earth Syst Sci 10:7–18

Akpan AE, Ibanga JI, George NJ, Ekanem AM (2019) Assessing seismo-ionospheric disturbances using Vanuatu and Honshu earthquakes of March 25, 2007, employing DEMETER and GPS data. Int J Environ Sci Technol 16(11):7187–7196

Bascıftcı F (2021) An analysis of the latest super geomagnetic storm of the 23RD solar cycle (May 15, 2005, Dst: -247 nT). Geomagn Aeron 61(Suppl 1):S156–S166. https://doi.org/10.1134/S0016793222010029

Basciftci F (2022) Investigating and comparing the two superstorms in the 23rd solar cycle. Indian J Phys 96(10):2707–2716. https://doi.org/10.1007/s12648-022-02396-y

Basciftci F, Bulbul S (2022) Investigation of ionospheric TEC changes potentially related to Seferihisar-Izmir earthquake (30 October 2020, MW 6.6). Bull Geophys Oceanogr 63(3):403–426. https://doi.org/10.4430/bgo00394

Berthelier JJ, Godefroy M, Leblanc F, Seran E, Peschard D, Gilbert P, Artru J (2006) IAP, the thermal plasma analyzer on DEMETER. Planet Space Sci 54:487–501

Bommer JJ, Crowley H, Pinho R (2015) A risk-mitigation approach to the management of induced seismicity. J Seismolog 19(2):623–646

Bulbul S, Basciftci F (2021) TEC anomalies observed before and after Sivrice-Elaziğ earthquake (24 January 2020, Mw: 6.8). Arab J Geosci 14:1077. https://doi.org/10.1007/s12517-021-07426-3

Chmyrev V, Smith A, Kataria D, Nestor B, Owen C (2013) Detection and monitoring of earthquake precursor. Twinsat, A Russia–UK satellite project. Adv. Space Res. 52(6):1135–1145

Davies R, Foulgera G, Bindleya A, Styles P (2013) Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. Mar Pet Geol 45:171–185

Dobrovolsky IR, Zubkov SI, Myachkin VI (1979) Estimation of the size of earthquake preparation zones. Pure Appl Geophys 117:1025–1044

Francesco M, Bizzarri A (2014) Anthropogenic triggering of large earthquakes. Sci Rep 4:6100. https://doi.org/10.1038/srep06100

Gupta HK (1983) Induced seismicity hazard mitigation through water level manipulation at Kryna India: a suggestion. Bull Seismolog Soc Am 73:679–682

Hayakawa M, Molchanov OA (2002) Seismo- electromagnetics: lithosphere atmosphere-ionosphere coupling. Terra Scientific Publishing Company, Tokyo, Tokyo

Ibanga JI, Akpan AE, George NJ, Ekanem AM, George AM (2017) Unusual ionospheric variations before the strong Auckland Islands, New Zealand earthquake of 30th September, 2007 NRIAG. J Astron Geophys 7:149–154. https://doi.org/10.1016/j.nrjag.2017.12.007

Klose CD (2013) Mechanical and Statistical evidence of the causality of humanmade mass shifts on the Earth's upper crust and the occurrence of earthquakes. J Seismolog 17(1):109–135

Lebreton JP, Stverak S, Travnicek P, Maksimovic M, Klinge D, Merikallio S, Lagoutte D, Poirier B, Kozacek Z, Salaquarda M (2006) The ISL Langmuir Probe experiment and its data processing onboard DEMETER: scientific objectives, description and first results. Planet Space Sci 54(5):472–486

Mayaud PN (1980) Derivation, Meaning and use of geomagnetic indices, Geophysical Monograph 22. American Geological Union, Washington DC

McGarr A (2014) Maximum magnitude earthquakes induced by fluid injection. J Geophys Res Solid Earth 119(2):1008–1019

Ondoh T (2008) Investigation of precursory phenomena in the ionosphere, atmosphere and groundwater before large earthquakes of M >6.5. Adv Space Res 43:214–223

Parrot M (2012) Statistical analysis of automatically detected ion density variations recorded by DEMETER and their relation to seismic activity. Ann Geophys 55(1):149–155

Píša D, Parrot M, Santolík O (2011) Ionospheric density variations recorded before the 2010 Mw 8.8 earthquake in Chile. J Geophys Res 116:A08309. https://doi.org/10.1029/2011JA016611

Rapoport Y, Grimalsky V, Hayakawa M (2004) Change of ionosphere plasma parameters under the influence of electric field which has lithospheric origin and due to radon emanation. Phys Chem Earth 29:579–587

Rozhnoi A, Solovieva M, Molchanov O, Schwingenschuh K, Boudjada M, Biagi PF, Maggipinto T, Castellana L, Ermini A, Hayakawa M (2009) Anomalies in VLF radio signals prior the Abruzzo earthquake (M = 6.3) on 6 April 2009. Nat Hazards Earth Syst Sci 9:1727–1732

Thomas JE (2020) Seismo- Ionospheric induced perturbations prior to the september 28, 2007 M7.5 Northern Mariana USA- geoquake from GPS-TEC and DEMETER data Malaysian. J Geosci (MJG) 4(1):38–42

Thomas JE (2021) Lithosphere-atmosphere -Ionosphere coupling fog Pre-, Co- and post earthquakes: a case study of Northern

Mariana, USA earthquake of 31st October 2007. Res J Sci Technol 1(1):37–46

Thomas JE, George NJ, Ekanem AM, Nathaniel EU (2020) Preliminary investigation of earth tremors using total electron content: a case study in parts of Nigeria. NRIAG J Astron Geophys 9(1):220–225. https://doi.org/10.1080/20909977.2020.1723866

Thomas JE, Ekanem AM, George NJ, Akpan AE (2021) Electron Temperature and Ion density perturbations prior to the M6.8 Eastern Honshu, Japan earthquake of July 23, 2008. J Earth Syst Sci. https://doi.org/10.1007/s12040-021-01645-8

Thomas JE, Ben UC, Ekanem AM, George NJ, Nathaniel EU (2022) Seismo Ionospheric anomalies before M7.2 Haiti earthquake of August 14, 2021, from GPS-TEC. Acta Geophys. 1–7

USGS (2015) United State Geological Survey. Earthquake Hazards Program, GPS data. Retrieved from URL. http://earthquake.usgs.gov/monitoring/gps/

Verdugo R, Gonzalez J (2015) Liquefaction- induced ground damages during the 2010 Chile earthquake. Sci Direct 79:280–295