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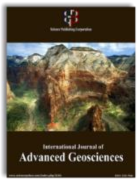

Ionospheric induced plasma disturbances afore the m7.9 eastern Sichuan china earthquake of 12th may, 2008

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Abstract

A great number of earthquakes occur yearly in different areas and almost 100 -120 of them have a magnitude above 5. These seismic activities are very harmful for the inhabitants. Findings reveal that this seismo-electro-magnetic abnormality is a mirror image of some processes, which originated a few weeks before the main event and stay until few days after it. Plasma ion analyser (IAP) and Instrument Sonde de Langmuir (ISL) sensors) experiments available on Detection of Electromagnetic Emissions Transmitted from Earthquake Regions (DEMETER) and Total Electron Content (TEC) from Global Positioning System (GPS) satellites, were employed to study the variations of electron and ion density for ionospheric disturbances before the M7.9 Eastern Sichuan China earthquake of 12th May, 2008. The study revealed seismo-ionospheric induced perturbations exactly three weeks afore the earthquake in all four investigated parameters. Electron density recorded 16.94 cm-3, electron temperature revealed - 2.25 o C while total ion density displayed 6.57 cm-1. The total electron content ranged from 4.28 to 3.6. The disturbance storm time (Dst) and planetary 3-hourly range (Kp) indices were used to classify pre-earthquake anomalies from the other anomalies associated with geomagnetic activities and was seen that this day (-21days relative to the earthquake) was devoid of geomagnetic storm, thus the observed perturbations were seismo-induced but not geomagnetic induced.

Keywords: *Ionosphere; DEMETER; GPS; Anomalies; Precursors.*

1. Introduction

The occurrence of Earthquakes is associated with the movement of Earth’s crust. The Earth's crust can be referred to as the rigid external shell of the Earth which consists of the continental and oceanic crust. The continental crust has thickness that is of order of 40000 m while that of the oceanic crust is closed to 6000 m. The entire crust as well as the upper mantle forms the lithosphere known to comprise the semi rigid plates characterized by varying sizes. According to Oreskes. 2003, the noticeable slow movement of various sizes of semi rigid plates over the ocean floor extension and the asthenosphere is known as plate tectonics. When these plates collide, it leads to diving of one plate edge under another (convergent or subduction boundaries). Process brings about the formation of various geological structures, which include, the formation of the oceanic trench in the zone of plates contact, formation of new mountains and zones of volcanic activity. Besides the subduction process, there are other kinds of plates relative motion such as plate separation (divergent boundaries), generating the oceanic crust, and transform boundaries which comes due to one plate moving over another. These movements result in the accumulation of damages such as mechanical deformations and crustal rupturing within the crust Earth. When the deformation goes beyond the limit of mechanical strength, the rupturing process is known as earthquake. The type and attributes of earthquake is dependent on the type of tectonic plate contact. Globally, the distribution of earthquakes is not uniform but concentrates mostly at the region of near the tectonic plate boundaries.

Earthquake is one of the dynamic natural occurring events that have great impact on Earth’s surface/atmosphere. The occurrence of earthquakes has proved to be hazardous to human life and properties. Due to the complexity of earthquake-preparation processes, identifying true earthquake precursors from anomalous geophysical signals is still a global problem. Also, seismic activity is one of the sources of the day-to-day ionospheric variability. This is related to the fact that the coupling between the anomalous generated electric field in the earthquake preparation zone at the ground surface and the one generated in ionosphere causes the ion drift that resulted in the modification of the ionosphere formation. Recently, earthquake occurrence has extended to unsuspected countries, regions and towns (e.g. Kaduna, Bayelsa and Kano in Nigeria). In these areas, there are no observatories or measuring device(s) to measure or predict the occurrence of the earthquake. Since ionosphere covers everywhere, therefore, studying the ionosphere in respect to earthquake prediction presents links as a result of generated electromagnetic field perturbations preceding earthquake events. Therefore, in order to predict the seismic event using the ionosphere the following question must be addressed: (i) Is there any change in the ionosphere due to pre-seismic event and aftermath event? (ii) Having understood that there are different mechanisms responsible for the plasma distribution in the ionospheric layers, what are the basic ionospheric drivers responsible for each stages of precursor, aftermath and during the earthquake? (iii) Is there any significant on latitudinal dependence of the ionospheric precursor, during and aftermath of earthquake in the ionosphere?Earthquakes occur prior to electromagnetic perturbations and it is believed that this seismo-electro-magnetic irregularity is an image of some developments which, began some weeks before the main event and subsist few days after it (Oraevsky et al. 1995;Ruzhin and Depueva, et al. 1996). Earthquake on its own is not disastrous but the secondary events it triggers, such as collapsed of building, fire and tsunamis are what really kill people.

In the preparation to an earthquake activity, a huge amount of energy is usually transferred due to crustal movement and at the instant of the shock, a break down occurs between the source of the energy and the environment. Studies have shown that these modifications before, during and after such events, do have different physical and chemical effects on the lithosphere, atmosphere and ionosphere (Pulinets and Boyarchuks, 2004; Chmyrev et al., 2013) thus making their detection possible. Consequently, perturbations in threshold state of lithospheric, atmospheric and ionospheric parameters can serve as earthquake indicators (precursor). This work assesses seismo-electro-magnetic induced perturbations in threshold conditions of the ionosphere before the magnitude 7.9 earthquake that occurred in Eastern Sichuan China of 12th May, 2008, as a short term precursor of it.

2. Materials and methods

Materials used in this work included data downloaded from websites of both ground and space observatories and information obtained from relevant literature. These data were acquired by satellites while screening the ionospheric-magnetospheric transition zone. Data used in the study included DEMETER data downloaded from DEMETER website (http://demeter.cnrs-orleans.fr//), GPS data downloaded from www.igs.org/network and geomagnetic data that were obtained from wdc.kugi.kyoto-u.ac.jp/cgi-bin/kp-cgi and wdc.kugi.kyoto-u.ac.jp/cgi-bin/Dst-cgi for the Kp and Dst respectively.

DEMETER is a microsatellite launched by the French Space Agency: Centre National D'etudesSpatiales (CNES) at about 06:30 UTC from Baikonour (Kazakhstan) on 29th June, 2004 aboard a Dnepr rocket launcher. Its transmission into space was done with a very high precision and it reached the required orbit with the following parameters: altitude of 709 km, inclination of 98^0, orbit period (100 min), orbits per day (14) (data available in half orbit) (Cussac et al., 2006). DEMETER was designed like a rectangular shaped box with dimensions of 60 x 85 x 11 cm and a total mass of 129 kg. DEMETER's orbit was polar, circular and nearly sun-synchronous and measurements were made at approximately two different local times 10:30 and 22:30 UTC (Kintner et al., 2013), (down or up and 1 or 0 may represent these times respectively.However, the altitude of this satellite was reduced to about 660 km in December 2005 and it was located onboard a Low Earth Orbit (500 to 2000 km in altitude) and visible for 10-20 minutes at a time (Parrot, 2012).

The scientific payload of the DEMETER has a three-axis magnetic search-coil instrument (IMSC), four electrical sensors (ICE), two Langmuir probes (ISL), a plasma analyzer (IAP), energetic particle detector (IDP) and electronic units (BANT). The IMSC captor was set at the end of a 1.9 m long boom while the ICE captors were kept at the extremes of four booms each 4 m long, to avoid electromagnetic disturbances to the sensors from the satellite (Hayakawa, 2016).

The DEMETER satellite mission ended on 9th December, 2010 but its data are archived at Centre de Données de la Physique des Plasmas (CDPP) and can be accessed through the web server (http://demeter.cnrs-orleans.fr//). The data are organized and plotted in half orbits. CDPP provides a huge array of data to investigate variations in electromagnetic emissions; production of plasma inhomogeneities and other ionospheric phenomena associated with seismic events. Its high sensitivity promotes the reliability of its data. In this research, data from the IAP and ISL sensors in the burst mode were used.

The instrument d' Analyse du plasma (IAP) unit generated a continuous record of the main parameters of the thermal ion population with two goals: (a) detection ofdisturbances in the ionosphere that may result from the coupling between seismic event on the ground and upper atmosphere and ionosphere, and (b) provision of sufficient time resolution for ionospheric parameters such as plasma density and ion composition required for the analyzes of plasma wave data obtained from ICE and IMSC experiments. The plasma analyzer instrument was carefully 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), their temperatures (from 500 – 5000K) and the ion flow velocity in the earth's frame reference (Berthelier et al., 2006).

The Langmuir probe experiment, technically called instrument Sonde de Langmuir (ISL), was designed for in-situ measurements of the bulk ionospheric thermal plasma parameters (Biqiang et al. 2008; Zeng, et al. 2009). This instrument had two sensors: a classical cylindrical sensor and a spherical sensor whose surface was segmented into seven sections (six electrically isolated spherical caps and other part of the sphere used as a guard electrode). The ISL experiment measured the electron density of plasma (10^8 – 5.10^{11} m^{-3}), electron temperature (600 -10,000 K) and satellite potential (~ ± 3V) in the ionosphere from which the relative ion and electron density along orbits of the DEMETER satellite were derived. Variations of these parameters were given with a time resolution of 1s (Berthelier, et al., 2006, Brien and Cornely, 2015).

The Global Positioning System (GPS) satellites have become primary sensors to measure signatures related with natural hazards such as earthquake. The huge network of GPS receivers (a few thousands all over the planet) explains simultaneous coverage in universal scale with high temporal resolution. Thus, TEC variations are often investigated for seismo- ionospheric precursors due to TEC data global analysis, continuous observation and satisfactory time- and space-resolution plus enormous amount of the data available. The GPS satellites transmit two frequencies of signals (LI=1575.42 MHz and L2=1227.60 MHz).These GPS receivers are capable of detecting ionospheric TEC perturbations caused by surface-generated Rayleigh, acoustic and gravity waves. Total Electron Content (TEC) is defined as the total number of electrons integrated along the path from the receiver to each GPS. TEC can be used to estimate spatial sizes and temporal dynamics of pre-earthquake ionospheric effects in any seismo-genic region (Klimenko, et al., 2011). TEC factor is predominantly associated with density in the F-layer which is greater than in the other layers (Sunil et al., 2015);providing an opportunity to detect any acoustic, gravity, or both types of waves perturbations in the upper atmosphere This technique has been used to identify perturbations due to an earthquake by Calais and Minster (1995).

Regional but significantly, large-scale changes in atmospheric electricity over seismically active zones before the seismic shock are transformed to the ionosphere by means of a large-scale electric field. From the penetration of this electric field into the ionosphere, electron concentration anomalies are observed when the region affected has an area with a diameter larger than 200 km (Dobrovolsky et al., 1979). However, the disparities in the ionospheric parameters are not only due to earthquakes as there are numerous possibilities of ionospheric distresses that can originate from other sources (solar activity, acoustic gravity waves, traveling ionospheric disturbances, plasma dynamics, and large meteorological phenomena). Consequently, the observed parameters may exhibit variations in the absence of seismic activity; hence, it is hard to isolate pre-seismic ionospheric phenomena from the ionospheric turbulences due to the solar-terrestrial activities (Ondoh, 2008). Thus, to differentiate the seismo-ionospheric perturbations from geomagnetic instabilities, the geomagnetic indices Dst and Kp were checked. The Kp index screens the planetary activity on a universal scale whereas the Dst index registers the equatorial ring current variations (Mayaud, 1980). The ionospheric influence of a geomagnetic storm has a global effect being observed all over the world while, the seismogenic impact is observed only by places with distance less than 2000 km from the potential epicenter (Pulinets et al., 2003).

Based on reported geographic coordinates regarding the earthquake epicenter, ionospheric parametersof electron density, electron temperature, total ion density and total electron content were extracted from DEMETER and GPS satellites 30 days before and 10 days after the seismic event. The Plasma Analyzer (IAP) and the Langmuir Probe (ISL) experiments data in the burst mode were used. The GPS station with the code XIAN was used. The radius of this area can be predicted using the Dobrovolsky formula $R = 10^{0.43M}$ where R is the radius of the earthquake preparation zone, and M is the earthquake magnitude (Dobrovolsky et al., 1979). Also, studies reveal that the irregularities in the electron concentration occur when the area on the ground surface occupied by the anomalous field exceeds 200 km in diameter. In the same vein, maximum of the affected area in the ionosphere does not coincide with the vertical projection of the epicenter of the impending earthquake and is shifted towards the Equator in high and middle latitudes (Pulinets et al., 2003). Therefore, it is preferable to process data recorded in satellite orbits close to epicenter during days before earthquakes. Accordingly, optimum value for distance between the satellite and the epicenter was selected in terms of DEMETER satellite altitude and earthquake zone radius.

The median m and the inter-quartile range (IQR) of data were used to create their upper and lower bounds in order to isolate seismic irregularities from natural variations. The upper X_H and lower X_L bounds of the data range were calculated using the following equations:

$$X_H = m + K \bullet IQR \quad (1)$$

$$X_L = m - K \bullet IQR \quad (2)$$

$$X_L < X < X_H \Rightarrow -K < \frac{X - m}{IQR} < K; \quad D_X = \frac{X - m}{IQR} \quad (3)$$

Where X, X_H, X_L and Dx are the parameter value, upper bound, lower bound and differential of x, respectively. Any perturbations outside these bounds were anomalous and had to be screened for seismo-ionospheric induced perturbations. To discriminate geomagnetic induced perturbations from seismo-genic variations, the geomagnetic indices of kp and Dst were checked within this time frame as displayed in Table 1.

3. Results and discussion

The DEMETER experiments revealed ionospheric perturbations in all three investigated plasma parameters of electron density, electron temperature and total ion density from both ISL and IAP sensors in Table 1. From the graph of each parameter against day relative to the earthquake day (a) night and (b) morning, anomalous variations were obtained. Considering the electron density measured in the night half orbits (Fig 1a(i)), three perturbations were obtained outside the upper and lower bounds on -28, -19 and -5 days prior to the seismic event with magnitude of 3.62, 2.37 and -3.07 respectively. However from the indices of geomagnetic activities, both Dst and Kp displayed solar activities on the 19th day before the earthquake (Fig 2b and 2c), thus the recorded perturbation on this day was geomagnetically induced. Having screened for geomagnetic induced variations, the remaining two recorded anomalies occurred during quiet solar activities and were possible indicators of the earthquake. In the same vein, the morning half orbits (Fig.1i(a)), presented four variations outside the bounds on -22, -21, -19 and -9 days having 2.65, 16.94, 2.31 and 4.58 correspondingly. The electron density rose from 2.65 to a very high value of 16.94 exactly three weeks before this event. This very high electron density happened in quiet geomagnetic period as both indices presented no solar activity. Thus it is pertinent to attribute such high concentration of the electron as seismic induced. Nevertheless, the variations of -19 were geomagnetically induced. The electron temperature of Fig.1ii (a and b) depicted both pre and post ionospheric irregularities. All anomalies recorded from this parameter happened in quiet geomagnetic period, as such were seismo-genic in nature. It is noteworthy that the post seismic perturbation occurred less than five days after the earthquake (Fig. 1ii (a)). This is consistent with the reports of Akhoondzadeh and Saradjian, (2011) and Akpan et al. (2019), which emphasized on the persisting of perturbations a few days after the main event. Investigations from the IAP device revealed that the total ion density (cm^{-3}) of the major ionospheric ions was the most disturbed parameter amongst the three quantities studied by the DEMETER data. A total of nine anomalous points were obtained with five being measured in the night time half orbits showing that the signals were better detected in the night time half orbits (Pulinets and Boyarchuk, 2004). The night readings showed only positive variations unlike the morning readings, which gave both positive and negative anomalies. All observed distortions occurred during quiet solar activity, except the perturbation of -19. These strongly suggests that the perturbed state of the ionospheric ions was not unconnected to the major seismic activity of 12th May, 2008, hence could have served as a precursor to this event. From the Differential Total Electron Content displayed on Fig 2a; by visual examination of the contour plots, perturbations are seen on the following days before the earthquake: -30, -28, -24, -22, -21, -20, -19, -18, -16, -19 and -3 between 05:00 hours and 13:00 hours. However, since the state of the ionospheric- magnetospheric transition zone is not ruled solely by large interior earth processes alone, the observed irregularities were screened for solar and magnetic influences. To this, from the indicator used, -30, -24, -19, -18, -16 and -9 were geomagnetically stormy. This is well presented by comparing Fig 2a withDisturbance Storm Time (Dst) (2b) and Kennziffer.digit (Kp) (2c) plots during this period. From the GPS TEC data, results presented showed anomalous TEC variations during some hours A correlation between the two sets of data used reveals that on -21 days (exactly three weeks before the earthquake), all four measured parameters (electron density, electron temperature, total ion density and Total electron content), presented anomalous variations under quiet geomagnetic condition. These clearly announced that a major seismic activity was on its way regarding the high magnitude of the recorded perturbations.In order to isolate geomagnetic perturbations from seismo-induced perturbations, the geomagnetic indices of kp and Dst were used. The DEMETER experiments detected anomalies on 12 days from the three ionospheric parameters investigated within this period. Of these anomalous variations, only that of -19 was geomagnetically induced as displayed by figure 2b & 2c. This gives about 9% of the observed perturbations. Hence the DEMETER experiments presented 91% of seismo-induced perturbations. Also comparing the TEC variations with the geomagnetic variations, a ratio of 67: 33 respectively was obtained. This is displayed in fig.2a. In all studied parameters, there was a distinct separation of seismo-induced perturbations from geomagnetic induced perturbations.

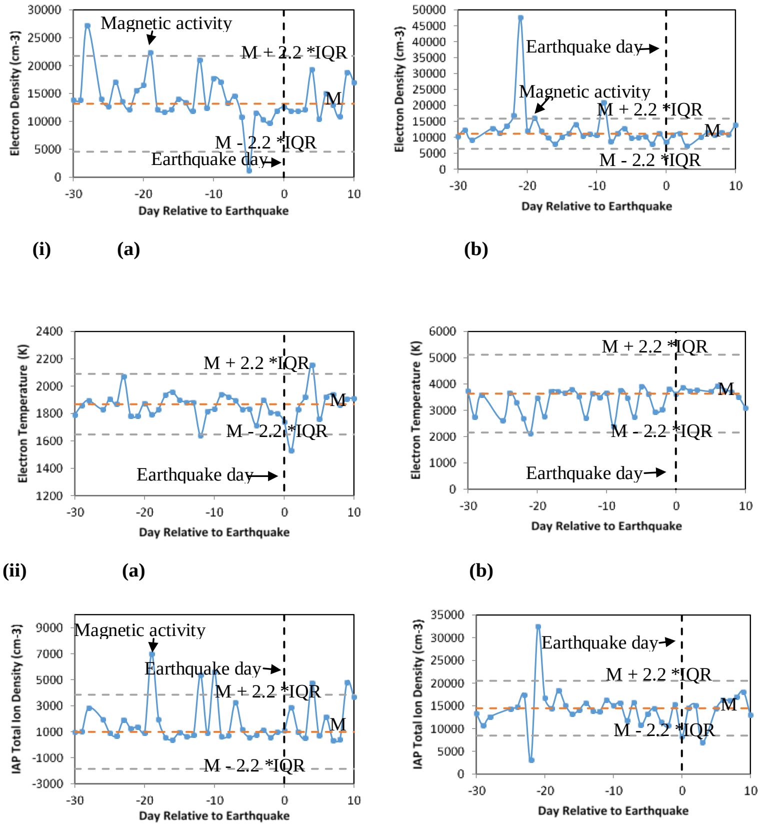

Fig.1. Results of DEMETER data analysis for the Eastern Sichuan China earthquake (12 May 2008) from 12th April to 22nd May 2008. The earthquake day is represented as vertical dotted black line. The purple horizontal lines indicate the upper and lower bounds (m±2.2*IQR). The pink horizontal line indicates the median value (m). The sudden variations related to the magnetic activity are indicated by an arrow. 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 by the measurements of the ISL experiment **(iii)** total ion density derived by the measurements of the IAP experiment (a) during night (b) during day.

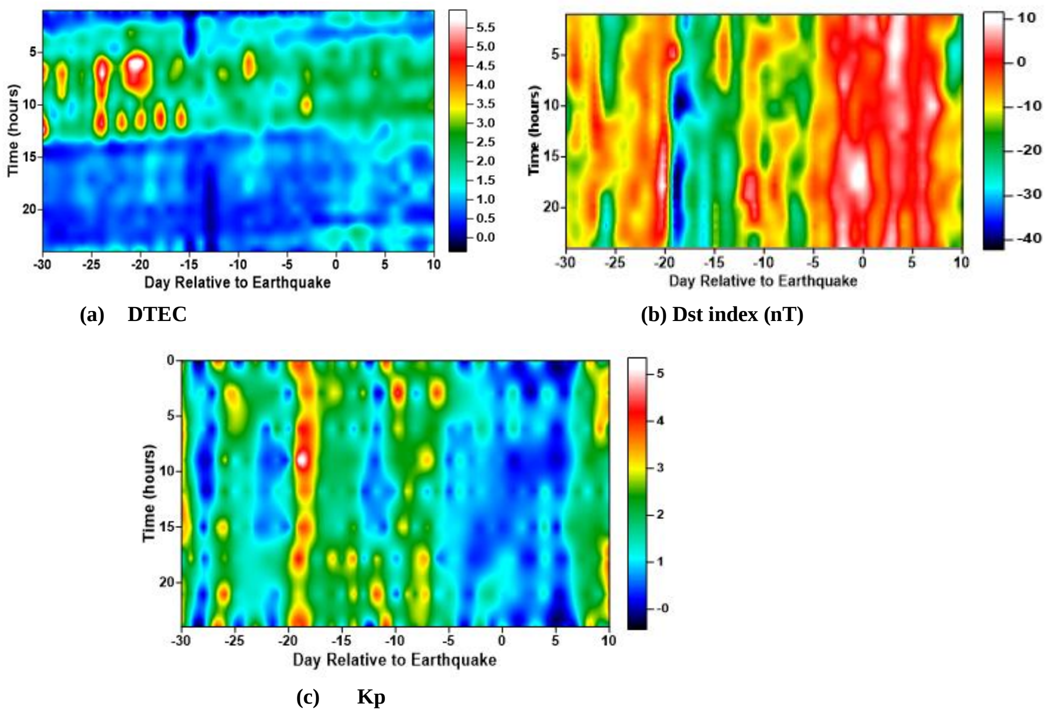

Fig. 2: Results of analysis for the Sichuan earthquake (12 May 2008) from 12th April to 22 May 2008. The x-axis represents the day relative to the earthquake day. The y-axis represents the time UTC (LT=UTC+08:00). **(a)** DTEC variations. **(b)** Variations of Dst geomagnetic index. **(c)** Variations of Kp geomagnetic index.

Table 1: Earthquakes and detected anomalies. Day is relative to the earthquake day. Value calculated by: $(x-m)/IQR$: 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 the earthquake is as follows: (DEMETER: $m \pm 2.2*IQR$; TEC: $m \pm 2.2*IQR$).

Location	Date	Time	TEC			DEMETER				Geomagnetic Indices		
			Day	Time	Value	Day	Value	Sensor	Parameter	Time	Kp	Dst
Eastern Sichuan, China	12/5/2008	6:28	-30	7:00	3.05	-28	3.62	ISL	Electron density	22:30	-30	-26
			-30	12:00	3.66	-22	2.65	ISL	Electron density	10:30	-26	-24
			-30	13:00	2.62	-22	-4.15	IAP	Total ion density	10:30	-19	-19
			-28	7:00	3.24	-21	6.57	IAP	Total ion density	10:30	-18	-18
			-28	8:00	2.67	-21	-2.25	ISL	Electron temperature	10:30	-16	-17
			-28	9:00	2.53	-21	16.94	ISL	Electron density	10:30	-14	-16
			-24	6:00	3.68	-19	4.63	IAP	Total ion density	22:30	-9	-15
			-24	7:00	4.74	-19	2.37	ISL	Electron density	22:30	-7	-14
			-24	8:00	3.74	-19	2.31	ISL	Electron density	10:30		-11
			-24	9:00	3.61	-12	-2.25	ISL	Electron temperature	10:30		-7
			-24	10:00	2.52	-12	3.39	IAP	Total ion density	22:30		9
			-24	11:00	3.59	-10	3.55	IAP	Total ion density	22:30		10
			-24	12:00	4	-5	-3.07	ISL	Electron density	22:30		
			-22	11:00	2.85	0	-2.26	IAP	Total ion density	10:30		
			-22	12:00	3.23	1	-3.36	ISL	Electron temperature	22:30		
			-21	6:00	4.28	3	-2.75	IAP	Total ion density	10:30		
			-21	7:00	3.64	4	2.91	IAP	Total ion density	22:30		
			-21	8:00	3.6	4	2.87	ISL	Electron temperature	22:30		
			-20	6:00	4.5	9	2.94	IAP	Total ion density	22:30		
			-20	7:00	3.11							
			-20	8:00	3.23							
			-20	11:00	3.14							
			-20	12:00	2.96							
			-19	8:00	2.5							
			-18	11:00	3.72							
			-18	12:00	3.24							
			-16	11:00	3.31							
			-16	12:00	2.93							
			-9	6:00	3.11							
			-9	7:00	2.8							
			-3	10:00	2.83							

4. Conclusion

Ionospheric plasma parameters have been investigated for seismo- induced perturbations before the strong Eastern Sichuan earthquake of 12th May 2008. The study revealed striking ionospheric perturbations in quiet geomagnetic conditions on 21 days before the said earthquake, suggesting such to be seismo-genic. These seismo-induced perturbations had both positive and negative values. The observed anomalous variations occurred within few weeks to days before the main event, hence serving as precursor and giving enough time for evacuation of life and property. This showed the reliability of these data as short term precursors and prediction of earthquake.

5. Declarations

Availability of data and materials: The data is available on request from the lead author.
Competing interests: The authors declare that they have no conflict of interest.
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Authors' contributions: Authors' Contribution Jewel E. Thomas and George N. George conceived the study, designed the framework and searched for DEMETER data. Aniekan M. Ekanem and Nsikak E. Ekpenyong used appropriate software programs to interpret the data while Nyakno J. George puts together the write up using the processed data and performed grammar checks as well as work on the references.

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