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Ionospheric anomalies associated with the Haiti earthquake of 12 January 2010 observed by DEMETER satellite

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Abstract. This paper examines the ionospheric anomalies around the time of a strong earthquake ($M = 7.0$) which occurred in Haiti region (18.457° N, 72.533° W) on 12 January 2010. DEMETER satellite data have been used to study the plasma parameters variation during the Haiti earthquake. One day (11 January 2010) before the earthquake there is a significant enhancement of electron density and electron temperature near the epicenter. Decrease of electron temperature is observed few days after the earthquake. Anomalous plasma parameter variations are detected both in day and nighttimes before the quake. Statistical processing of the DEMETER data demonstrates that satellite data can play an important role for the study of precursory phenomena associated with earthquakes.

1 Introduction

The Haiti earthquake was a seismic event with a magnitude 7.0 and epicenter near the town of Léogâne, approximately 25 km west of Port-au-Prince, Haiti's capital. The earthquake occurred at 16:53 local time (21:53 UTC) on Tuesday, 12 January 2010. By 24 January, at least 52 aftershocks measuring 4.5 or greater had been recorded.

It is now believed that non-seismological methods are also helpful to work out the strategy for earthquake prediction. A major interdisciplinary effort is needed to develop a prediction scheme based on multi-premonitory phenomena, which means that near field of future focal zone must be first identified and then monitored for electrical, magnetic acoustic, seismic, and thermal precursors simultaneously and continuously (Molchanov et al., 2004). Various kinds of phenomena have been observed in the atmosphere and ionosphere above the seismo active areas during earthquakes. These phenomena, in a broader category, involves studies related to electric and magnetic field changes, nightglow observations, electron and ion density variations in the ionosphere (Pulinets, 2004), thermal anomalies as precursors of earthquakes (Tronin et al., 2002; Pulinets et al., 2006) and generation of electromagnetic waves (Parrot et al., 1993).

Launch of the DEMETER (Detection of Electromagnetic Emissions Transmitted from Earthquake Regions) satellite on 29 June 2004 has provided a good opportunity to study the ionospheric perturbations associated with earthquakes. DEMETER was placed in a polar, circular and quasi sun-synchronous orbit (10:30 and 22:30 LT) at an altitude of 710 km (reduced to 660 km since December 2005) and an inclination of 98.3° at the end of June 2004. The DEMETER satellite has been designed specifically to search for possible ionospheric precursors of earthquakes. Several case studies have shown that ionospheric signatures associated with earthquakes often appeared over the region near the epicenter within a short time period before earthquakes (Parrot and Mogilevsky, 1989; Serebryakova et al., 1992; Chmyrev et al., 1996; Trigunait et al., 2004; Parrot et al., 2006; Sarkar et al., 2007, 2011; Sarkar and Gwal, 2010, Liperovskaya et al., 2011). Many anomalous phenomena have already been recorded by DEMETER and reported by several workers (Parrot et al., 2006; Sarkar et al., 2007; Zhang et al., 2009; Akhoondzadeh et al., 2010).

Data from different experiments can be used to study the precursors of earthquakes. Electron density and temperature data from the ISL experiment onboard DEMETER have been used to study the ionospheric changes before the great Haiti earthquake. We have found interesting changes in ionospheric parameters during the Haiti earthquake.

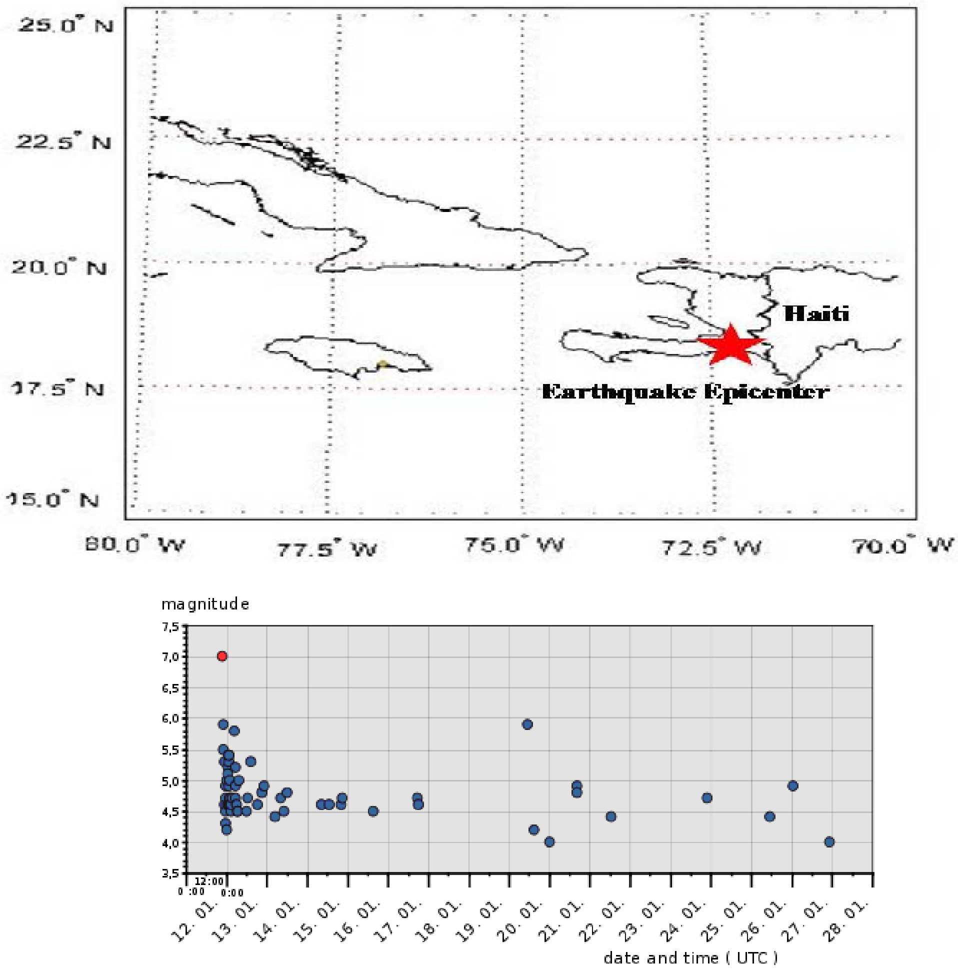

Fig. 1. Map showing the epicenter of the Haiti earthquake (downloaded from www.earth.google.com) in the upper panel. Magnitude and occurrence of the main aftershocks are shown in the lower panel.

2 Study area

Haiti occupies the western part of the island of Hispaniola, one of the Greater Antilles islands situated between Puerto Rico and Cuba. Haiti lies just to the south of the boundary between the Caribbean and North American plates; near Haiti the boundary is transform, but eastward towards the Dominician Republic, Puerto Rico and the Lesser Antilles (Sykes and Ewing, 1965). The 12 January 2010 Haiti earthquake occurred in the boundary region of the Caribbean plate and North American plate. The Caribbean plate is moving eastward with respect to the North American plate at a rate of 20 mm yr°. Haiti is surrounded by a long indent coastline which is seismically active. The location and focal mechanism of this earthquake are consistent with the event having occurred as left-lateral strike slip faulting on the Enriquillo-Plantain Garden fault system. This fault system accommodates about 7 mm yr^{-1}, nearly half the overall motion between the Caribbean plate and North American plate, basically two major east-west trending, strike-slip fault systems: the Septentrional fault system in northern Haiti and the Enriquillo-Plantain Garden fault system in southern Haiti (http://earthquake.usgs.gov/).

Haiti has experienced many earthquakes in historic times and some of the more severe ones. This latest Haiti earthquake did not produce any surface rupture, so it is expected that some of the energy must be stored in the uppermost few kilometers of the fault (Bilham, 2010). Figure 1 shows the epicenter of Haiti earthquake along with the magnitude and occurrence of the main aftershocks.

3 Data and methodology

There are several sensors onboard DEMETER to survey the ionosphere. The electron density and temperature variations are studied using the Langmuir Probe Instrument (ISL). The Langmuir Probe Experiment (ISL) is designed to measure the

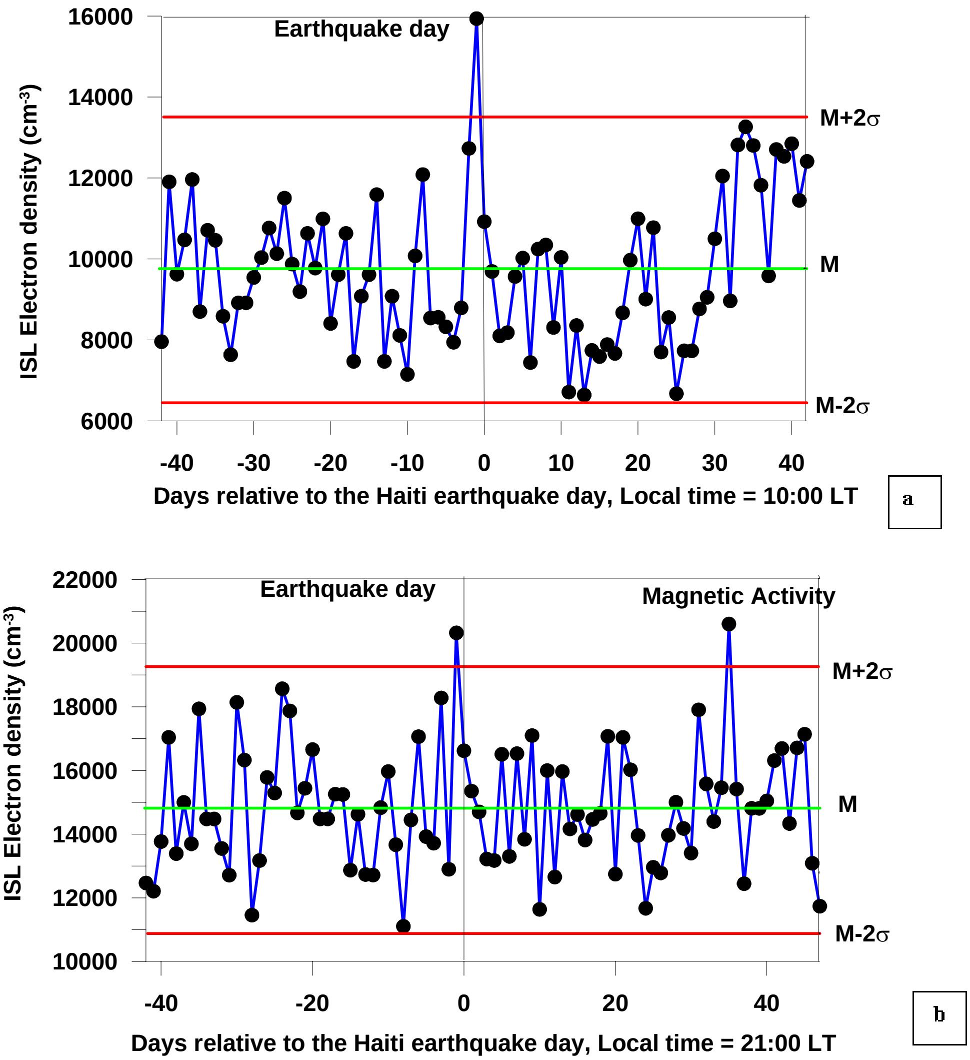

Fig. 2. Results of DEMETER analysis for Haiti earthquake from December 2009 to February 2010. Earthquake day is represented as vertical dotted line. The red horizontal lines indicate the upper and lower bounds. The green horizontal line indicates the mean value (M). The x-axis represents the day relative to the earthquake day. The y-axis represents **(a)** electron density derived by the measurements of the ISL experiment during daytime and **(b)** electron density derived by the measurements of the ISL experiment during nighttime.

electron density of plasma (in the range 10^8–$5 \cdot 10^{11}$ m^{-3}), electron temperature (in the range 600–10 000° K) and the potential of the satellite (in the range $\sim \pm 3$ V). Variations of these parameters are obtained with a time resolution of 1 s (Lebreton et al., 2006). In this study, data of ISL experiment in both survey and burst modes have been analyzed. Data and plots are available by half-orbits through a web server (http://demeter.cnrs-orleans.fr).

The median and standard deviation have been used to construct the lower and upper bounds in order to separate the seismic variations from the background normal variations. The 2σ (σ is the standard deviation) method is being used as the statistical criterion. In calculating the statistical parameters, data of 90 days have been analyzed from December 2009 to February 2010. Upper and lower bounds of the mentioned range have been calculated using the following equations:

$$\mathrm{xhigh} = \mathrm{M} + 2\sigma \quad (1)$$

$$\mathrm{xlow} = \mathrm{M} - 2\sigma \quad (2)$$

M represents the mean value. An electron density perturbation is considered as an anomaly if it exceeds the M+2σ value or if it is lower than the M-2σ. Using the 2σ criterion we can say with 95 % confidence level that the electron density value will lie within M$\pm 2\sigma$ interval.

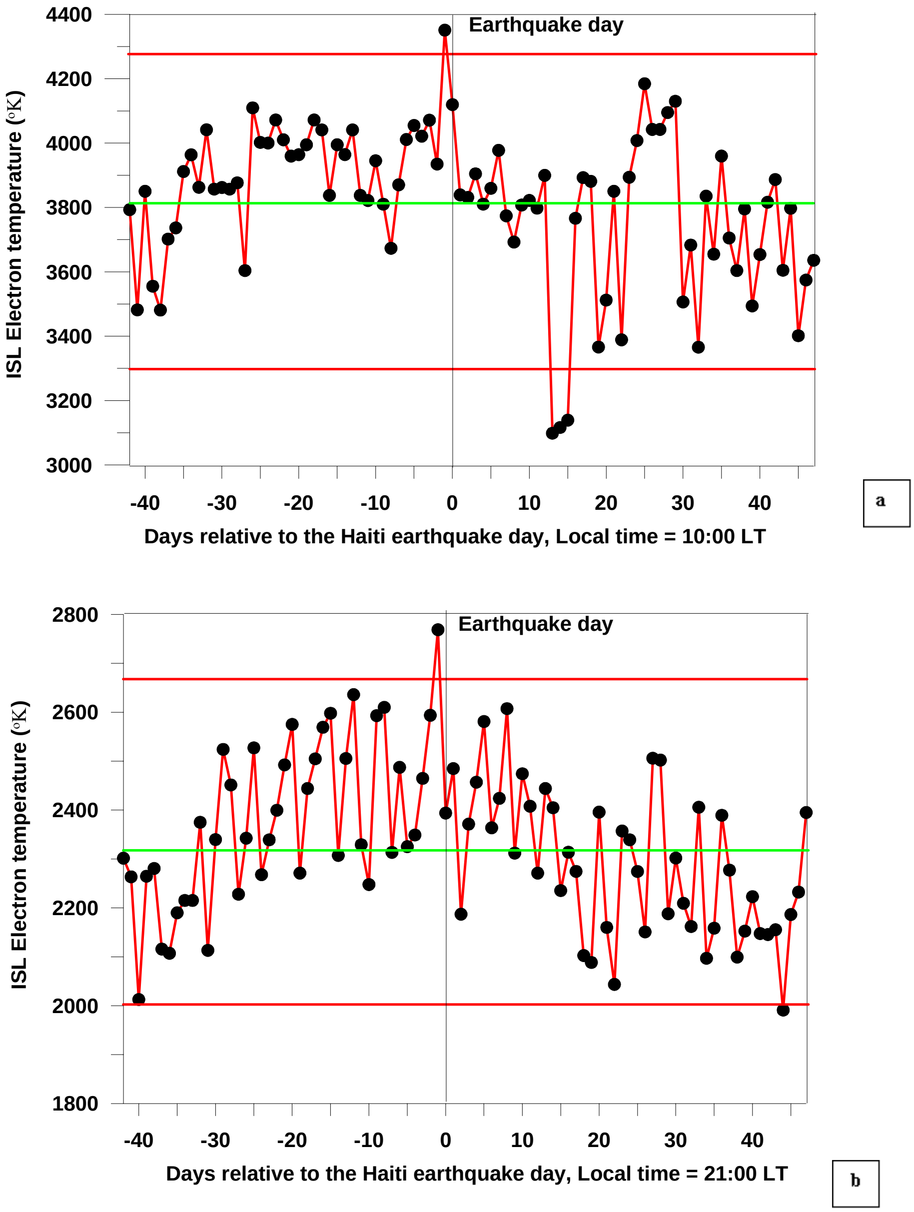

Fig. 3. Results of DEMETER analysis for Haiti earthquake from December 2009 to February 2010. Earthquake day is represented as vertical dotted line. The red horizontal lines indicate the upper and lower bounds. The green horizontal line indicates the mean value (M). The x-axis represents the day relative to the earthquake day. The y-axis represents **(a)** electron temperature derived by the measurements of the ISL experiment during daytime **(b)** electron temperature derived by the measurements of the ISL experiment during nighttime.

4 Results and discussion

Figure 2a illustrates daily averaged electron density recorded from ISL experiment during daytime (10:00 LT) from December 2009 to February 2010 for all orbits available in the latitude range 10° N to 30° N and longitude range 280° E to 300° E. Mean and bounds (upper and lower) are seen as green and red horizontal lines, respectively. Variation of electron density clearly exceeds the upper bound (M+2σ) on 11 January 2010, one day before the earthquake. The transition in electron density value from the upper bound is of the order of 20 %. On the same day, nighttime (21:00 LT) averaged electron density values also exceed the upper bound by 9 % as can be seen from Fig. 2b. It is worth mentioning here that Liu et al. (2011) have observed a similar enhancement in Total Electron Content (TEC) over the epicenter on 11 January 2010. They have used the global ionosphere map (GIM) to detect seismoionospheric anomalies.

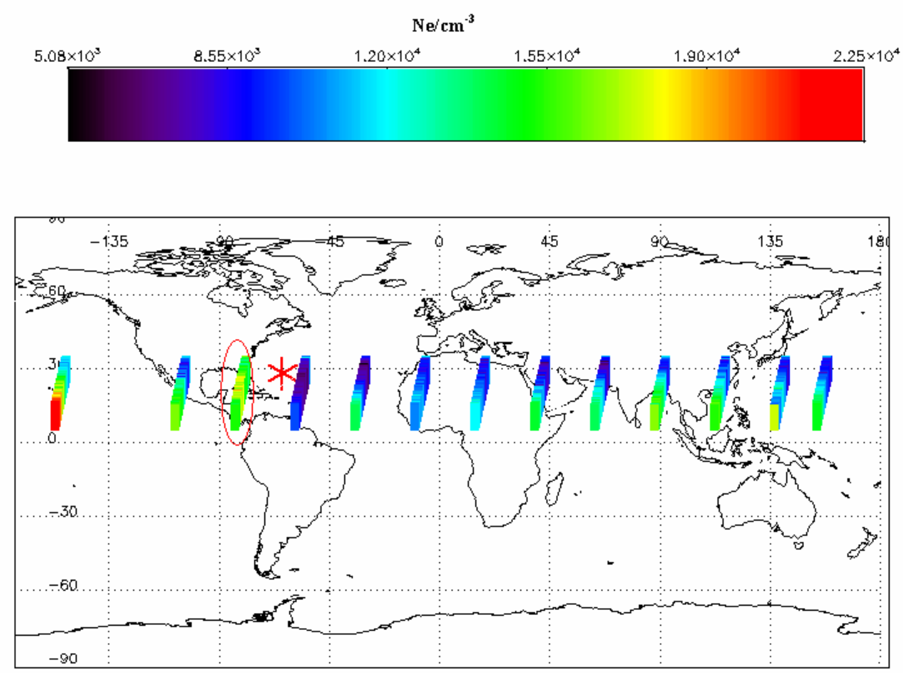

Fig. 4. Electron density distribution around the globe during daytime on 11 January 2010. Star shows the epicenter of the Haiti earthquake.

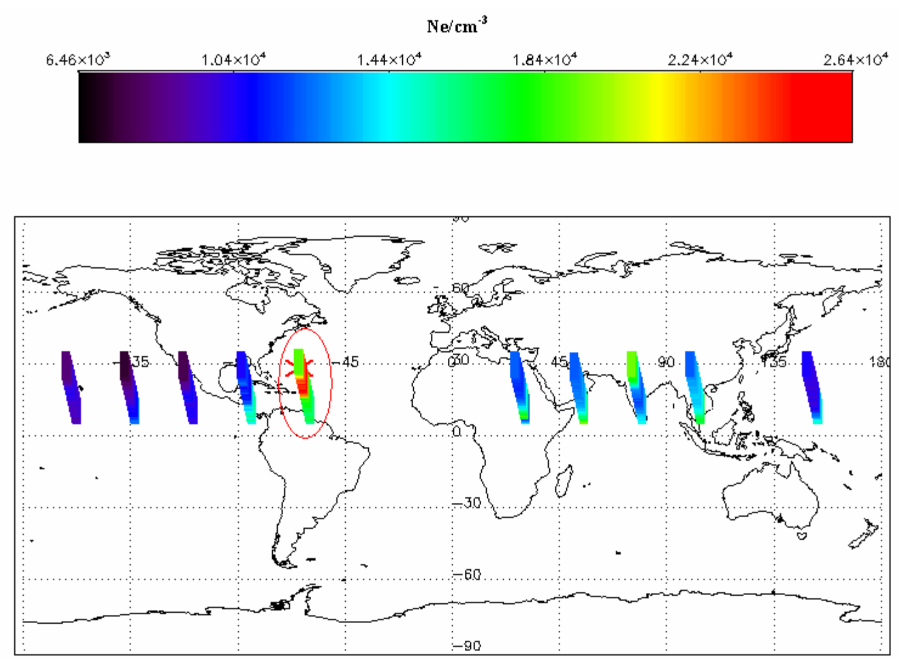

Fig. 5. Electron density distribution around the globe during nighttime on 11 January 2010. Star shows the epicenter of the Haiti earthquake.

Another density variation which can be seen on 16 February 2010 in Fig. 2 was due to magnetic activity, as 16 February was international disturbed day. Electron temperature data recorded from the ISL experiment also shows similar variations on 11 January 2010 (Fig. 3a and b). Both daytime and nighttime values exceed the upper bound as shown in Fig. 3a and b, respectively. However, a decrease in electron temperature below the lower bound was observed from 25 to 27 January during daytime (Fig. 3a). This may be due to the aftershock activity. Electron density data for all the orbits around the world recorded at local daytime (10:00 LT) and local nighttime (21:00 LT) on 11 January 2010 are shown in Figs. 4 and 5, respectively. The spatial shape of electron density is consistent around the globe and increase of electron density can be clearly seen near the epicenter of the Haiti earthquake during daytime and nighttime. During daytime a perturbation is seen near the epicenter $\sim 1.76 \times 10^4$ el.cm^{-3} (shown by red circle in Fig. 4). An increase of electron density $\sim 2.2 \times 10^4$ el.cm^{-3} is observed near the equator around $-157°$ longitude far away from the epicenter, which is not due to the earthquake but due to equatorial anomaly. During nighttime a strong perturbation (shown by red circle in Fig. 5) is observed near the epicenter $\sim 2.6 \times 10^4$ el.cm^{-3}. Singh et al. (2010) studied surface (surface air temperature) and atmospheric (relative humidity, surface latent heat flux) parameters during the Haiti earthquake. A low surface temperature was observed one day prior to the earthquake, and soon after the earthquake they found the surface temperature to increase. Also, one day prior to the earthquake event (11 January 2010) they found a pronounced anomaly of relative humidity, the peak being more prominent as compared to other peaks in relative humidity observed in other years. All these observations suggest a coupling between the lithosphere-atmosphere and ionosphere during the Haiti earthquake. Pulinets and Ouzonov (2010) suggested that all of them have the common root – radon emanation and air ionization. Most of the phenomena observed before earthquakes have a common physical mechanism. Also, synchronization in timing is observed for the atmospheric anomalies and the ionospheric anomalies. In the case of the Haiti earthquake, the ionospheric anomalies observed by us and also by other researchers occur in conjunction with atmospheric anomalies one day before the main shock (11 January 2010). Atmospheric and ionospheric anomalies are observed within the interval of 1 day. Plasma parameters variation obtained from DEMETER satellite clearly show anomalies prior to the Haiti earthquake over the region of impending earthquake. These ionospheric disturbances can be explained by the atmospheric electric field drops due to increase in atmospheric conductivity caused by ionising influence of radon escaping from the fault zone. Pulinets et al. (2000) have demonstrated how the seismic electric field can penetrate into the ionosphere. This electric field leads to the formation of irregularities in the ionosphere and thereby affecting the electron density distribution in the ionosphere (Pulinets et al., 1998). Even small changes of ionospheric electric field can substantially modify the concentration of O^+ at heights of the F2 layer maximum before earthquakes (Pulinets and Boyarchuk, 2004). They have reported several examples in which modification of the O^+ ion and of light ions H^+ and He^+ were found above the region of anticipated earthquakes. The data of DEMETER satellite have also been used to study the variation of plasma parameters associated with strong earthquakes in the mid latitude region (Sarkar et al., 2007). Significant changes of the electron density were marked near the epicenter of anticipated earthquakes. Pulinets et al. (2004) showed increased ionosphere variability around the time of the seismic shock at ionospheric stations close to the impending earthquake epicenter position. In our case, also maximum irregularity intensity is observed for the orbits near to the epicenter. The ion density anomalies were registered during nighttime DEMETER passes and not during daytime. Pulinets and Boyarchuk (2004) have demonstrated that the efficiency of penetration of electric field is greater at night than in daytime. Also, the anomalies registered before the main shock are not above the vertical projection of the epicenter but are located eastward. It is known that maximum of the affected zone of the ionosphere does not coincide with the vertical projection of the epicenter of the future earthquake (Pulinets and Legen'ka, 2003).

5 Conclusions

During the Haiti earthquake we have shown the occurrence of interesting density variations. The main characteristics of these observations must be underlined:

– The plasma density pre-earthquake anomalies were observed one day before the earthquake both during daytime and nighttime as can be seen from Figs. 2 to 5. These variations can be considered as short term precursors to the Haiti earthquake. The most important variation is observed one day before the main shock in the form of density and temperature changes. Electron density exceeded the upper bound by 20 % and 9 % during day and nighttime, respectively. Electron temperature is known to be closely related to electron concentration in the F2-region, and the latter in its turn is strongly affected by electric fields. The possible mechanism of the enhancement of electron density is discussed by Pulinets (1998), which is also supported by experimental evidence. The main source of atmosphere-ionosphere coupling over the epicenter zone is the emanation of different chemical substances like radon, light gases, and submicron gases from Earth (Alekseev and Alekseeva, 1992). They change the electrodynamic properties of the atmosphere over the epicenter zone. In the presence of aerosols, the electrode effect enhances the electric field up to several kV/m and this field then penetrates into the ionosphere where, due to anisotropic conductivity, they transform into horizontal fields (Kim et al., 1994). The perturbations of the electric field can manifest themselves up to ionospheric altitudes and cause changes of ionospheric electron density.

– Both daytime and nightime passes of DEMETER satellite show the presence of anomaly near to the epicenter one day before the main shock.

– Additional anomaly observed from 25 to 27 January in the form of decrease in electron temperature below the lower bound maybe due to aftershock activity.

– Ionospheric and atmospheric anomalies have been observed by other researchers also during the same time period (Liu et al., 2011; Singh et al., 2010), which confirms our observations.

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