J. Ind. Geophys. Union (April 2014)
v.18, no.2, pp:195-204

Ionospheric precursors of M9.0 Tohoku earthquake on March 11, 2011

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ABSTRACT
An earthquake of magnitude M 9.0 hit the Japan on 11th March 2011. The earthquake triggered one of the deadliest tsunamis. We analyzed the temporal variation of ionospheric parameters ten days before and five days after the main shock. These parameters measured by the ground based Ionosonde characterize the state of ionosphere. We have used the data of Kokubunji Ionosonde station, which lies at a distance of 440 km from the epicenter of the earthquake. The data analysis revealed a sharp enhancement in the height parameters hmF2, h/F2 and h/F of F layer seven days prior to the main shock, while critical frequency of F2 layer foF2 showed a slight decrease. We also examined the variation of electron density (NmF2), Ionospheric Electron Content (IEC) and ionospheric slab thickness parameters and found that while slab thickness increased around the same time the values of NmF2 and IEC underwent a decrease. Since the ionosphere was raised to higher heights the density decreased correspondingly. We also performed the cross correlation analysis of the Kokubunji station with other stations of Japan. From this analysis we found that on 3rd March 2011 Kokubunji followed a negative correlation with other stations of Japan.

INTRODUCTION

Natural events like earthquakes, tsunamis and volcanic eruptions are inevitable and unpredictable. Therefore, it is one of the major challenges felt presently by the scientific community world over to find a reliable seismic precursor. The researchers have started efforts in this direction a couple of decades ago. In case of an earthquake rupture, certain precursory activity can be expected, if the observation is made in the near vicinity of causative rupture. These precursory activities may include radon and helium emanation, electromagnetic emissions, water level and temperature changes, ground uplift and tilt and changes in ionospheric parameters.

Global efforts to predict earthquakes were started about a century ago and peaked during 1970s. The first scientifically well documented earthquake prediction was made on the basis of temporal and spatial variation of ts/tp relation in Blue mountain Lake, New York on 3rd August 1973 (Aggarwal et al., 1975). Seismologists then successfully predicted the Heicheng China earthquake of 4th February 1975 (Cha Chi Yuan), which raised the hopes that it could be possible to make reliable earthquake forecasts. The seismologists have now narrowed down their studies from long term prediction to short term prediction.

Among the different precursory phenomena mentioned in the publications on earthquake prediction, the ionospheric ones are youngest. It has been now established that ionosphere is not only sensitive to solar influences, but it is also affected by lithospheric processes. The occurrences of some specific phenomena at different altitudes and in different layers of ionosphere are believed to be caused by lithospheric processes happening prior to a seismic event. The researchers are of the view that there is a perfect connection between lithosphere and ionosphere, which may be established either from ground or from space. Above the epicenter of future earthquake, macroscopic changes can appear in the ionospheric parameters at an altitude between 400 km to 1000 km. There are many evidences of seismic associated ionospheric disturbances (Hayakawa and Fujinawa, 1994; Parrot et al., 2006). The first publication concerning seismic associated ionospheric effects came just after Alaska Good Friday earthquake in 1964 (Davies and Baker, 1965; Moore, 1964). Since then a wide range of ionospheric-seismogenic phenomena have been acquired by in-situ satellite and ground based measurements. Sobolev and Husamiddinov (1985) reported increase in foF2 two days before the main shock while Fatkulin et al. (1989), reported a decrease in foF2 before the main shock. Similar results have been obtained by Pulinets et al. (2006), and Liu et al. (2004). Satellites have registered specific variations and plasma disturbances associated with earthquakes (Rodger et al., 1996; Pulinets, 2004). In addition, the plasma density and ion composition were also analyzed and reported by Boskova et al. (1993).

Ionospheric perturbations linked with earthquakes have also been studied extensively by number of researchers (Parrot and Hobara, 2005; Parrot et al., 2006; Singh et al., 2004). These are due to propagation of acoustic gravity waves which interact with ionosphere as suggested by first seismo-ionosphere coupling mechanism (Yuen et al., 1969; Birfeld, 1973). Attempts have also been made to study and establish lithosphere-ionosphere coupling (Liperovsky et al., 1991; Shalimov and Gokhberg, 1998; Hayakawa and Molchanov, 2002).

Total Electron Content (TEC) from GPS has also proved to be a useful tool in studying ionospheric effects associated with earthquakes (Liu et al., 2004; Devi et al., 2004). It has been found that smooth variation in TEC is replaced by rapid fluctuations during a seismic activity. Ground based measurements of ionospheric perturbations associated with seismic activity have also been carried out with ionosondes (Chou et al., 2002; Pulinets et al., 2004; Dutta et al., 2007).

THE TOHOKU EARTHQUAKE

The 2011 Tohoku, Japan earthquake took place (coordinates of the epicenter: 38.32ºN, 142.36°E) at 05:46: UTC on Friday, the 11th March 2011 (JST = 14:46). The magnitude of this earthquake was 9.0 (Mw, moment magnitude) and the focal depth was 32 km. The epicenter of the earthquake was located under sea waters, approximately 72 km east of Oshika Peninsula and about 129 km east coast of Honshu. Sendai was the nearest major city to the earthquake, 137 km from epicenter. It may have occurred due to thrust faulting on or near the subduction zone plate boundary between the Pacific and North American plates. This earthquake occurred where the Pacific Plate is subducting under the plate beneath northern Honshu. The Pacific plate, which moves at a rate of 83 mm/ year, dips under Honshu. This motion pulls the upper plate down until the stress builds up enough to cause a seismic event. An earthquake of such high magnitude usually requires a rupture length of at least 480 km and a long and relatively straight fault surface. When the plate boundary and subduction zone in the area of the rupture is not very straight, it is unusual for the magnitude of an earthquake to exceed 8.5. As such, the higher magnitude of this earthquake came as a surprise.

DATA AND ANALYSIS OF IONOSPHERIC PARAMETERS

To study the ionospheric perturbations caused by this earthquake we used the Ionosonde data of Kokubunji station (35.7°N, 139.5°E). The distance of the station from the epicenter (38ºN, 142ºE) is 440 km (Figure-1). This station is closest to the epicenter compared to, other three stations Okinawa, Yamagawa and Wakanai.

Regular radio soundings are made from a network of stations across Japan, since last couple of decades. The data is made available to public at National Institute of Information and Communication (NICT) website at:

http://wdc.nict.go.jp/IONO/HP2009/ISDJ/index

The NICT Ionosonde data contains 15 minute and hourly averaged values both in manually scaled and automatic scaled mode. For the present study we have used the manually scaled hourly averaged values of height parameters and critical frequency of F2 layer (foF2) over Kokubunji station. For the event, a time interval of ten days before and five days after the event is taken into account. The ionospheric electron content (IEC) data was taken from the National Geophysical Data Center (NGDC) website at:

http://spidr.ngdc.noaa.gov/

From the values of foF2 we calculated the peak electron density (NmF2) of F2 layer by using the relation:

$$NmF2 = 1.24^{*} (foF2)^2 \text{ X } 10^{10} \text{ electrons/m}^3$$

Where, foF2 is the critical frequency of F2 layer in MHz.

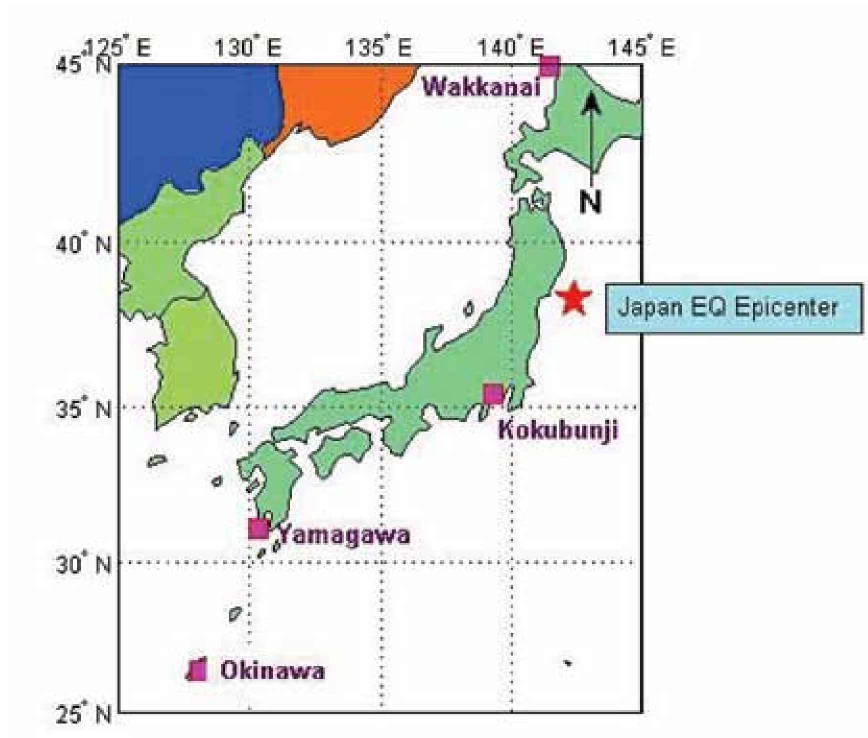

Figure 1. Map of Japan showing location of M 9.0, Tohoko earthquake epicenter and four Ionosonde station of Japan (Prepared in MatLab)

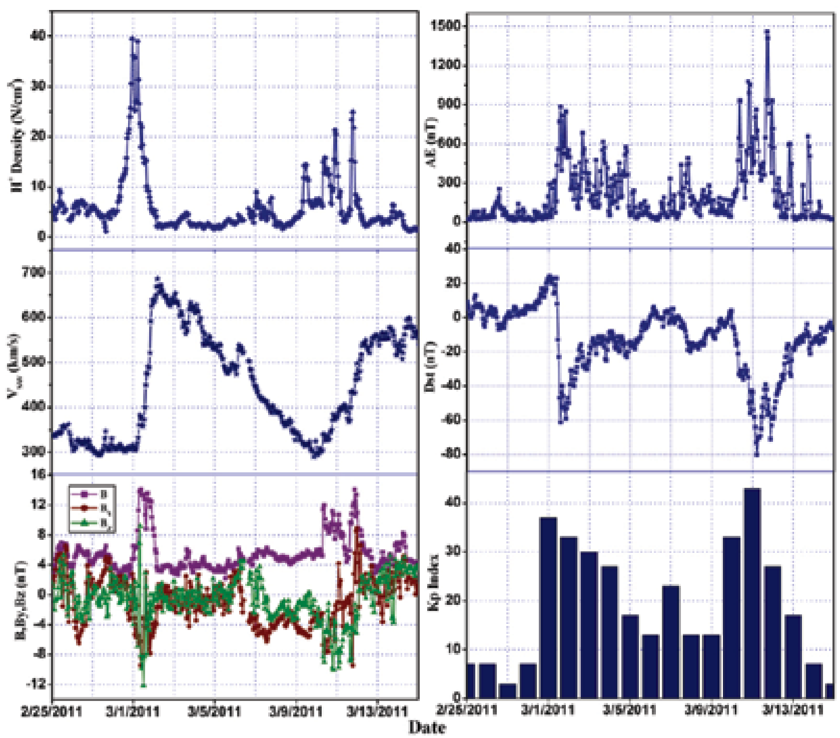

Figure 2. Variation of solar, geomagnetic and interplanetary indices during 25th February 2011 to 15th March 2011. The B, By and Bz in the legend stand for Interplanetary Magnetic Field components i.e north-south component (Bz), East-west component (By) and total magnitude (B).

The slab thickness was calculated as the ratio of NmF2 and IEC i.e.,

$$\text{Slab thickness } (\tau) = \text{IEC/NmF2}.$$

Where, τ is slab thickness in km, IEC is the ionospheric electron content (10^{16}el/m^2) and NmF2 is peak electron density (10^{10}el/m^3) of F2 layer.

Ionospheric effects of earthquakes are usually superposed by solar and geomagnetic disturbances. Therefore, it is imperative to know the geomagnetic conditions during the period of study. For this we have plotted the variations of various solar, interplanetary and geomagnetic parameters viz., interplanetary magnetic field (IMF) components, solar wind density, solar wind velocity, Dst, Kp and AE to check the geomagnetic conditions at the time of event. The variation of these parameters is shown in Figure-2. From this figure, we could see that the earthquake occurred between two geomagnetic storms (moderate) one on 1st March 2011 and the other on 11th March 2011. However, at the time of precursory changes the effect of storms had decreased and magnetic activity had comparatively decreased.

RESULTS AND OBSERVATIONS

The analysis of the ionospheric data over Kokubunji for earthquake preparation period showed seismogenic association of ionospheric effects. We studied first the variation of height parameters. Figure-3 shows the variation of hmF2 (Peak height), h$^{/}$F2 (Virtual height) and h$^{/}$F parameters from 1st March 2011 to 15th March 2011. Usually the values of hmF2 were between 200 km and 400 km but on the 3rd March 2011 the values went up to 611 km (encircled blue), indicating a sharp unusual enhancement. Similar enhancement was observed in the h$^{/}$F2 and h$^{/}$F. The two geomagnetic storms that occurred during this period was almost of the same magnitude (moderate) and it could be seen that these storms produced the same magnitude (in pink squares) effect on the height parameters. But the changes associated with earthquake were quite sharp and unusual. The similar type of height enhancement is also reported by Maruyama et al. (2011), using the ionogram signatures recorded at four Japanese stations during the same earthquake. They also found that the distortion in ionograms existed only at Kokubunji station, the closest to epicenter.

The critical frequency of F2 layer is important as it is also sensitive to seismogenic effects, apart from solar and geomagnetic effects. The variations of critical frequency of F2 layer (foF2) are presented in Figure-4. We notice clearly the departure from the normal behavior on 3rd March 2011. The values of the foF2 showed a decrease seven days prior to the main shock. The values of NmF2 (peak electron density of F2 layer) showed a much pronounced decrease (Figure-5). Although decrease of foF2 is not much pronounced, the decrease of electron density is remarkable. We also plotted the variations of ionospheric electron content (IEC) for the same period (Figure-6). Here, again, we found that the values of IEC on 3rd March 2011 are less compared to other days. Figures-5 and 6 also exhibit the same type of variance, thus confirming the specific trend. Using the GPS derived Total Electron Content (TEC) Tsugawa et al. (2011), reported depletion in the TEC. Thus, TEC and IEC derived through two different techniques (GPS and Ionosonde) reflect the same observation. This supports our observations.

To confirm the enhancement of height parameters we calculated the slab thickness (Figure-7). It is clearly seen that the values of slab thickness showed a sharp and unusual increase on 3rd March 2011. As the ionosphere was raised to higher heights the slab thickness increased accordingly. Thus, Figure-7 reflects the same result as shown in the Figure-3.

To ascertain that these changes are truly associated with earthquake, we performed cross correlation analysis of Kokubunji station with other stations of Japan, namely, Okinawa, Yamagawa and Wakkanai. The correlation analysis is summarized in Figure-8. From this figure, we found that on 3rd March 2011 the correlation of Kokubunji with other stations decreased remarkably. As Kokubunji is closer to the epicenter, its varied results confirm that the changes were associated with seismic event of 11th March 2011. According to Pulinets et al. (2004), the cross correlation of daily variations with critical frequency (or vertical TEC) can reveal ionospheric precursors even during geomagnetic disturbances. The ionospheric variation observed at two stations due to solar and geomagnetic effects are usually similar, if the two stations fall under the same geophysical conditions or the distance between the two stations is small. However, the seismic associated ionospheric disturbances are registered by the closest station only (Pulinets and Boyarchuk, 2004). Similar

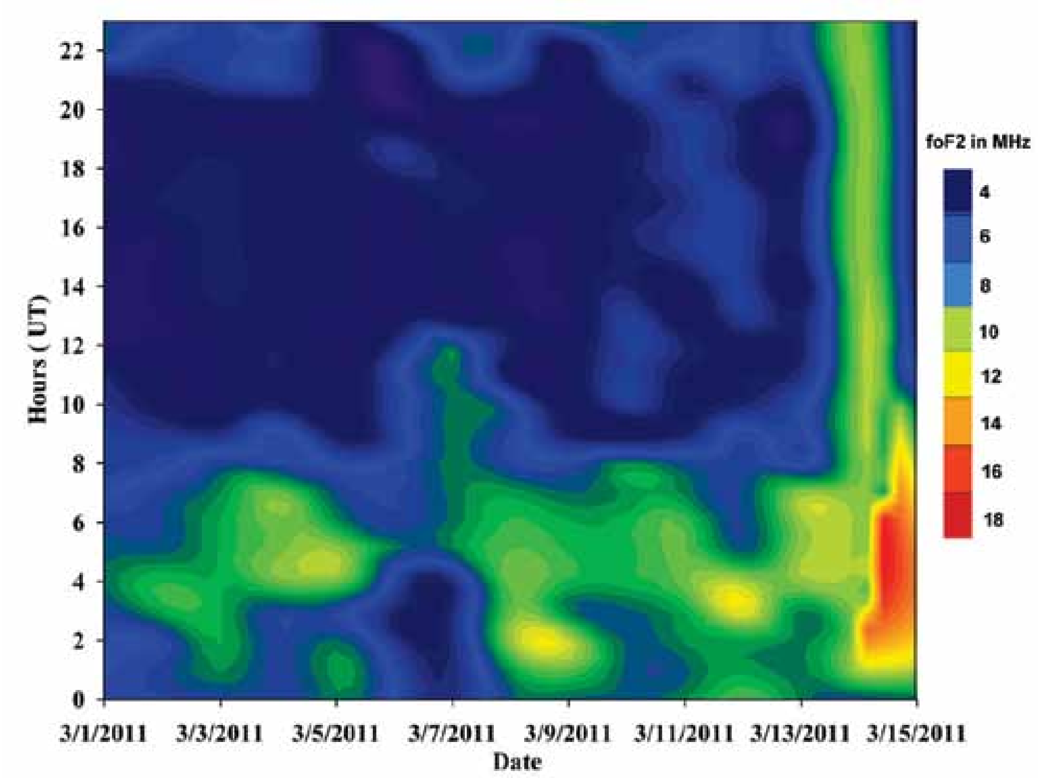

Figure 4. Variation of critical frequency (foF2) of F2 layer at Kokubunji station during 1st March 2011 to 15th March 2011

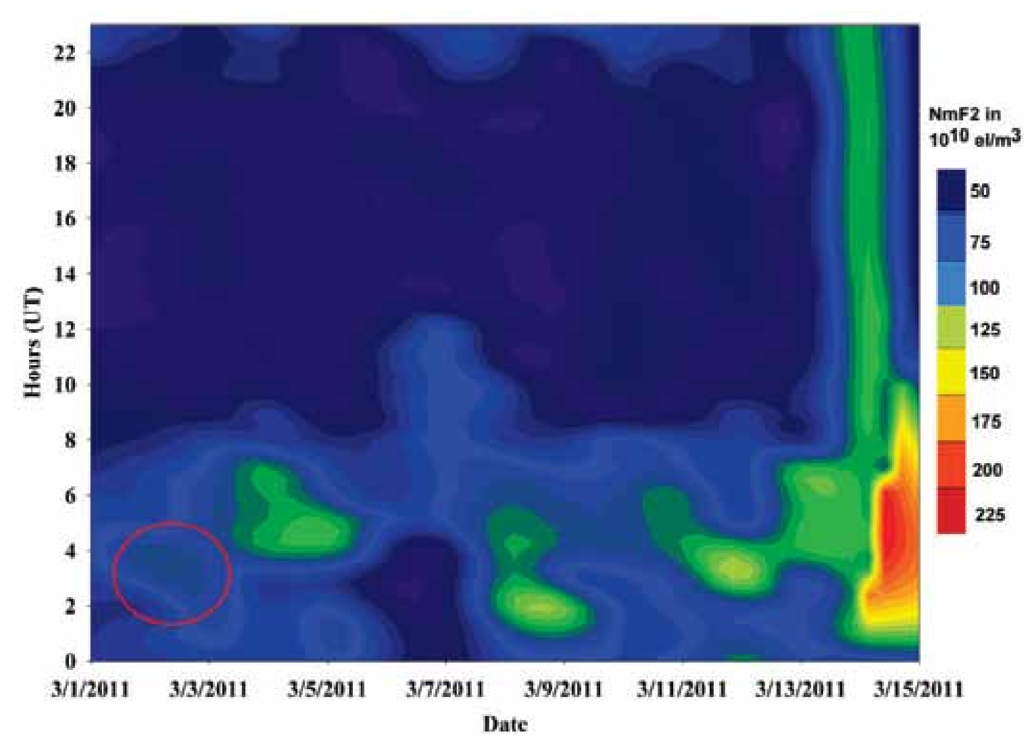

Figure 5. Variation of peak electron density (NmF2) of F2 layer over Kokubunji station during 1st March 2011 to 15th March 2011

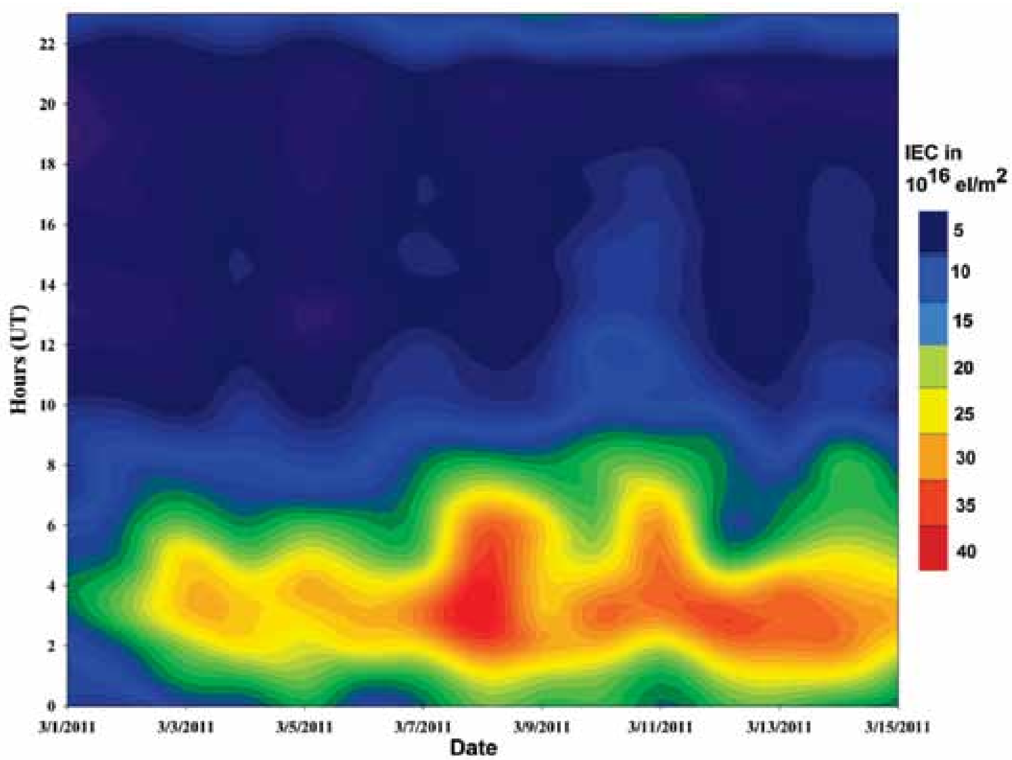

Figure 6. Variation of ionospheric electron content (IEC) over Kokubunji station during 1st March 2011 to 15th March 2011

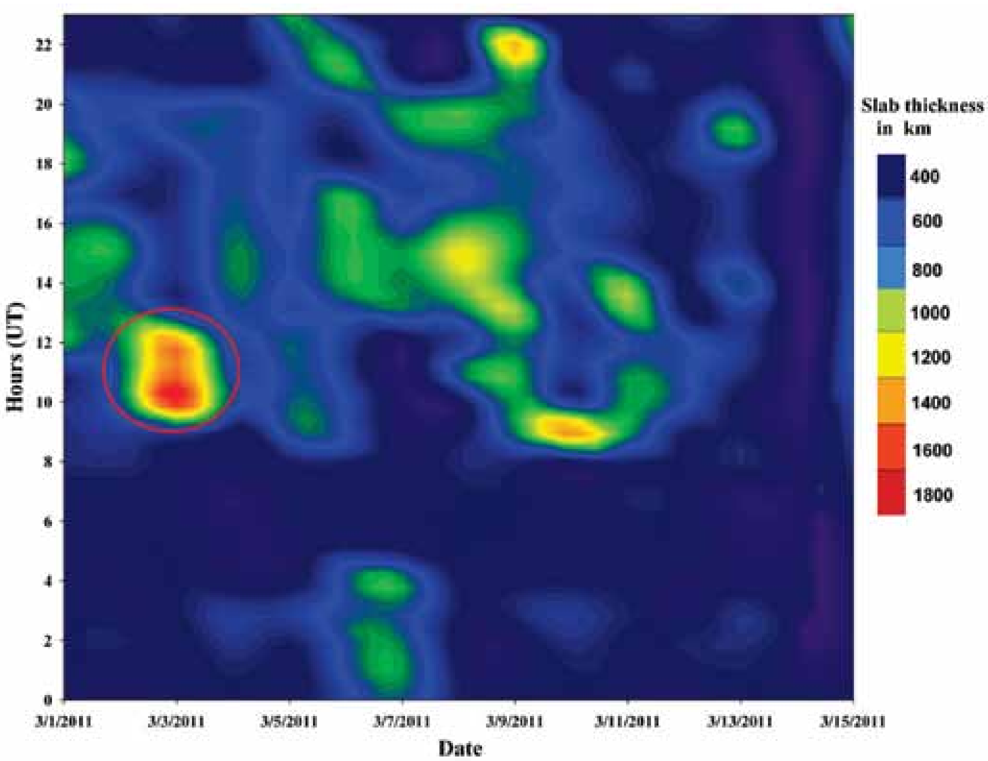

Figure 7. Variation of slab thickness over Kokubunji station during 1st March 2011 to 15th March 2011

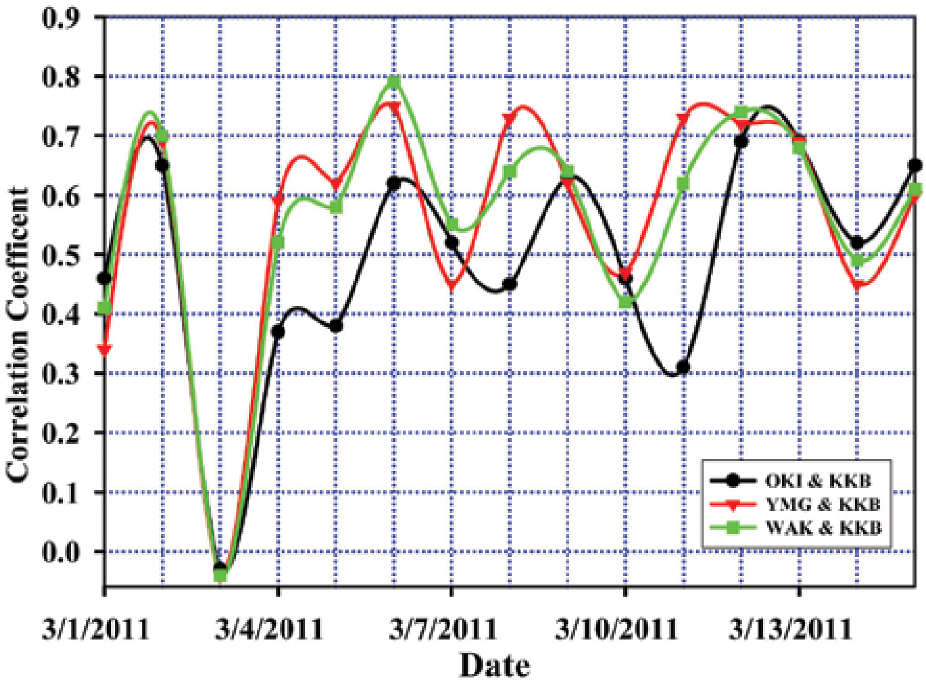

Figure 8. Cross correlation of Kokubunji staton with other stations of Japan. The acronyms in the legends are OKI for Okinawa station, KKB for Kokoubunji, YMG for Yamgawa and WAK for Wakani

to our analysis Ouzounov et al. (2011) also applied the cross correlation technique for the Tohoku earthquake of 11th March 2011 and reported the drop of correlation between Kokubunji and Yamagawa stations, before this seismic event.

DISCUSSION

It is generally believed that during the earthquake preparation period stress on the rocks increases considerably. The rocks respond to such a phenomenon by emitting electrons due to which electromagnetic and geophysical fields get altered to a certain extent. These alterations/ changes affect the atmosphere and ionosphere around the earthquake zone in one way or other. There are two popular theories on how earthquakes affect ionosphere: one pertains to effect due to gravity waves, which are generated in the earth and propagate to the ionosphere and the other is associated with the vertical electric field that connects earth with ionosphere. These earthquake-atmosphere-ionosphere coupling mechanisms may affect, before the earthquake, crustal movement causing gravity oscillations, which may spread to the ionosphere in the form of gravity waves. The piezoelectric field produced by the crustal deformation before earthquakes, may connect up to the ionosphere and modulate the dynamo electric field and redistribute the plasma.

Both the above stated mechanisms were found to be operating during the preparation period of Tohoku earthquake (Liu and Sun, 2011; Ouzounov et al., 2011). Liu and Sun (2011) observed three modes of Sudden Traveling Ionospheric Disturbances (STIDs) during the same Tohoku earthquake. These STIDs might have been induced in the ionosphere by Rayleigh waves, acoustic gravity waves or tsunami waves of the earthquake. Liu and Sun (2011) also determined velocities 2100-3200, 900 and 200 m/s for Rayleigh Waves, acoustic gravity waves and tsunami waves, respectively. These high speed waves in the ionosphere might have been induced by the vertical motion of the earthquake waves.

The Lithosphere-Atmosphere-Ionosphere coupling mechanism (Pullinets and Ouzounov, 2011) can provide the physical links of atmospheric and ionospheric variations with tectonic activity. The increased emanation of radon or other gases from the Earth's crust in the vicinity of active fault can cause ionization of air and hence can change the conductivity of air due to latent heat release. The ionosphere immediately reacts to these changes in the electric properties of the ground. Ouzounov et al., (2011) have reported a thermal build up around the epicentral area of the Tohoku earthquake due to increased emanation of radon and other gases. This might have triggered the ionospheric disturbances on getting coupled with the ionosphere.

CONCLUSIONS

Using the ground based Ionosonde data we conclude our findings as following. The Tokohu earthquake emitted precursory signals, which caused a sharp unusual and abnormal enhancement in the height of F layer ionosphere. These enhancements were accompanied by a decrease of density parameters. The decrease in density parameters was noticed in spite of a geomagnetic disturbance. The cross correlation analysis confirmed that the changes in ionospheric density and height parameters were associated with earthquake and not with geomagnetic disturbance.

ACKNOWLEDGEMENTS

The authors are highly thankful to (1) National Institute of Information and Communications (NICT), Japan, for making Ionospheric data of Kokubunji station available on its website, (2) National Geophysical Data Center (NGDC), for IEC data downloaded from its website, (3) OMNI data web for geomagnetic and solar indices data, (4) ACE mission team for solar wind and IMF data, (5) USGS for providing earthquake related information, and (6) University Grants Commission, New Delhi, India, for providing fellowship to SC and PK through SAP programme.

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