J. Ind. Geophys. Union (January 2016)
JIGU Special Volume-2/ 2016 pp: 127-132

Preliminary studies of ionospheric behavior during a seismic event of Mw~6.9 at Qinghai station (geog. 33.19° N, 96.75°E)

Malini Aggarwal[1*], D. K. Sharma[2] and Ananna Bardhan[2]
Indian Institute of Geomagnetism, New Panvel, Mumbai, India
Department of Physics, Manav Rachna University, Faridabad, India
asmalini@rediffmail.com

ABSTRACT
The prediction of one of the natural hazards, namely, earthquakes continues to be most challenging for earth scientists. Several recent studies have shown examples from different regions of the world, by which an association noticed between possible electromagnetic precursors and earthquakes has become more authentic. We have investigated the response of ionospheric parameters to the seismic conditions for one of the seismic events of 13 Apr 2010 (Mw~6.9, depth~13.8 km) over Qinghai station (**geog. 33.19° N, 96.75°E**), using the available online information from the US Geological survey (USGS) website for seismic and space-based GPS-TEC (GPS based total electron content) measurements, for the ionospheric behaviour. The preliminary result shows anomalous depletions in GPS-TEC observed 3-4 days before the seismic event in the ionosphere over nearby stations: Lhasa, Kunming and Urumqi consecutively for ~7-10 hrs.

Keywords: Ionosphere, Seismo-ionosphere coupling, GPS-TEC.

INTRODUCTION

Since last few decades, a connection between the earthquake (EQ) phenomena and the earth's ionosphere is proposed and many scientific investigations have been carried out to understand if it exists, using various satellite and ground-based measurements (eg. *Pulinets et al.,1998; Pulinets and Boyarchuk, 2004; Liu et al., 2009*). But still the ambiguity of seismo-ionospheric effects exists and the conclusions are not very clear. This is because the EQ phenomenon is a complex chain of various physical processes, which reflects the physical nature of different geochemical, atmospheric, ionospheric and magnetospheric anomalous variations (*Pulinets and Ouzounov, 2011*). Along with this, the earth's ionosphere also exhibits the day-to-day, seasonal, longitudinal, latitudinal and annual variabilities, which mainly are driven by solar activity. Apart from the solar-driven variations, 27 day variations (*Kakinami et al., 2009*), the ionospheric variabilities existed due to the dynamics of thermosphere and occurrence of a variety of geophysical phenomena like planetary waves, atmospheric and lunar tides etc. The occurrence of a geomagnetic storm also changes the ionospheric behavior, which changes the background conditions during disturbed period (*Afraimovich and Astafyeva, 2008; Astafyeva and Heki, 2011; Aggarwal et al., 2013*). Recently, *Le et al., 2013* investigated the ionospheric behaviour using GPS-TEC measurements prior to the 11 Mar 2011 Tohoku-Oki EQ and found a significant increase in TEC adjacent to the epicenter and its magnetic conjugate for 16 hr on 8 Mar 2011. This was considered to be related to the EQ and the geomagnetic disturbances on 7 Mar (Kp=4). Besides the storms, it was recently shown that even under geomagnetically quiet conditions and during low solar activity, a decrease of the Bz component of the IMF to -5 nT is enough to produce ~15-25% increase in the equatorial afternoon TEC (*Astafyeva and Heki, 2011)*. *Pulinets and Boyarchuk (2004)* explained the variations of near-earth plasma densities observed over seismically active areas several days/hours before strong seismic shocks. They demonstrated the seismo-ionospheric coupling to be a part of the global electric circuit and the anomalous electric field observed in the active seismic areas to be the main carrier of information from the earth's ground surface to the ionospheric altitudes. Besides this, another factor considered responsible for the co-seismic disturbances is the atmospheric gravity waves (AGWs). These waves are produced by the vertical sudden displacement of the ground and sea surface caused by the EQ and tsunami (*Watada et al., 2009*). Considering the various complexities, we probed the ionospheric behaviour during a seismic event (Mw~6.9, depth~13.8 km) of 13-14 Apr, which occurred at Qinghai (geog. 33.19° N, 96.75°E) station in China to study and understand the changes in the physical ionospheric behavior before the EQ event.

THE EQ DESCRIPTION

The strong EQ of magnitude 6.9 occurred on 13 Apr, 2010 around 23:49:38 UT (14 Apr 2010 around 07:49:38 LT) and its aftershock (14 Apr 2010, 6.1 magnitude, ~ 01:26:16 UT) at the epicenter (geog. 33.19°N, 96.75°E, geom. 23.90°N, 169.98°E), with shallow depth ~13.8 km in the Southern Qinghai, China (as reported on the United State Geological Survey (USGS) website *www.earthquake.usgs.gov.in*). This EQ occurred as a result of strike-slip faulting in the tectonically complex region of the eastern

Tibetan Plateau and is one of the largest known historic earthquakes within several hundred kilometers of its location. The radius of the earthquake preparatory zone in the lithosphere is found to be ~930 km. This was obtained by using the expression, R = 10^(0.43M), where M is the magnitude of the earthquake (*Dobrovolsky et al., 1979*).

DATA SET AND ANALYSIS

To investigate the spatial and temporal irregular behavior of the ionosphere before and during the earthquake event, the hourly total electron content (TEC) is obtained by the GPS using 10 IGS stations in the Chinese sector, by using a method of thin layer approximation (~350 km) (*Klobuchar, 1986*) with >20° elevation angle to minimize the time shift and avoid unwanted errors due to multipath (*Aggarwal et al., 2012*). The GPS-TEC is defined as the total number of electrons from the ground to the height of GPS satellite (20,500 km) in 1 m^2 area. **Figure 1(A)** shows the location of the epicenter (starred) and the relative distance of the considered GPS receivers (symbol). The stations considered are: Lhasa (LHAZ, geog. 29.65°N,91.1°E), Kunming (KUNM, 25.02°N, 102.79°E), Urumqi (URUM, 43.8°N, 87.6°E), Wuhan (WUHN, 30.53°N, 114.35°E), Fangshan (BJFS, 39.6°N, 115.89°E), Sheshan (SHAO, 31.9°N,121.2°E), 2 stations at Hsinchu (24.79°N, 120.98°E, TCMS and TNML), Taoyuan (TWTF, 24.95°N, 120.98°E) and Changchun (CHAN, 43.79°N, 125.44°E). The circle represents the preparatory or influence zone of the earthquake of radius ~930 km. Out of these stations, we found that LHAZ lies in the preparatory zone of earthquake, whereas KUNM is just at the boundary. The three stations (BJFS, CHAN and URUM) are further north of Qinghai, whereas others are toward the equator side. The LHAZ and URUM lie in the west, whereas other stations are in east-side of the epicenter. To compare the behavior of ionosphere away from the occurrence of EQ event, 6 more IGS stations are considered: Chumysh (CHUM, 42.99°N, 74.75°E, Kazhakstan), Kitab (KIT-3, 39.14°N, 66.88°E, Uzbekistan), Ulaanbataar (ULAN, 47.67°N, 107.05°E, Mongolia), Tehran (TEHN, 35.69°N, 51.33°E, Iran), Suwon-Shi (suwn, 37.27°N, 127.05°E) and Daejeon (DAEJ, 36.39°N, 127.37°E) in South Korea, respectively. All these stations are also shown in **Figure 1 (A)**.

To detect abnormal signals in the GPS TEC, we used the method of *Liu et al. (2009)*,which is gaining significance in determining the possible EQ precursors (e.g *Astafyeva and Heki, 2011; Pundhir et al., 2014*). We computed the hourly median M, lower (first) quartile (LQ) and upper (third) quartile (UQ) for the successive previous 15 days of GPS-TEC for same UT over each station. Under the assumption of a normal distribution with mean (m) and standard deviation (s) for the GPS TEC, the expected values of M and LQ or UQ are noted as m and 1.34s, respectively (*Klotz and Johnson,1983*). Then the isolated TEC anomalies are obtained as the lower bound (LB)=M-1.5(M-LQ) and upper bound (UB)=M+ 1.5(UQ-M), respectively. Here, the probability of observed TEC in the interval (LB, UB) is approximately 65%. Thus when an observed TEC (Obs) on the 16th day is found to be higher or lower than its previous 15-day-based median by UB or LB, we confirmed presence of an upper or lower abnormal GPS TEC signal.

RESULTS AND DISCUSSION

The earth's ionosphere is subjected to numerous influences, from both above as well as below due to the variability of solar activity, geomagnetic activity, meteorological events, and anthropogenic effects. The ionosphere also exhibits normal day-to-day, seasonal and diurnal variations making it difficult to identify possible pre-seismic ionospheric anomalies (*Afraimovich and Astafyeva, 2008*). Hence, we also firstly looked into the prevailing background conditions during our study period. The **Figure 1(B)** represents the variability of Dst (storm-time disturbance) and F10.7 (solar flux) in the upper panel along with the observed TEC, M, LB and UB on each day over LHAZ, KUNM, URUM and CHAN stations during 5-14 Apr 2010. Though we obtained the TEC variabilities over each station, only 4 stations are shown here (**Figure 1 (B)**).Out of which CHAN is farther station in China, whereas other 3 stations are near the epicenter.

A coronal mass ejection (CME) occurred on 3 April 2010 and arrived at the earth 2 days later (*Mostl et al., 2010*). On 5 April 2010, an interplanetary (IP) shock was detected by the Wind spacecraft ahead of Earth, followed by a fast (~ 650 km/s, average speed) IP CME. This CME was associated with a magnetic cloud. A moderate geomagnetic storm occurred that lasted 3 days (5-7 April 2010). The Kp index became higher ~7.7 (0900-1200 UT) on 5 Apr with Dst min (~-81 nT) on 6 Apr around 1500 UT. Despite being a relatively moderate storm, it nevertheless had some devastating space weather impacts, including the malfunction of the Galaxy 15 communication satellite (at ~35,785 km) (*Allen, 2010*) and widespread GPS scintillations ranging from the Arctic to Antarctic (*Prikryl et al., 2011; Kinrade et al., 2012*). *Smirnov et al., (2014)* studied the effects on the electric parameters of the amospheric near-ground layer during this storm. They found that air electro-conductivity decreased by a factor of 2, 4 hrs before the sudden commencement (SC) of storm and lasted for 20 hrs. The storm's SC caused potential gradient oscillations with amplitudes up to 300 V/m. This storm was associated with higher solar flux (F10.7~76-79 sfu) as compared to other days during our study period. Another weaker storm occurred on 11-12 Apr with Dst min ~-67 nT around 0200 UT on 12 Apr.

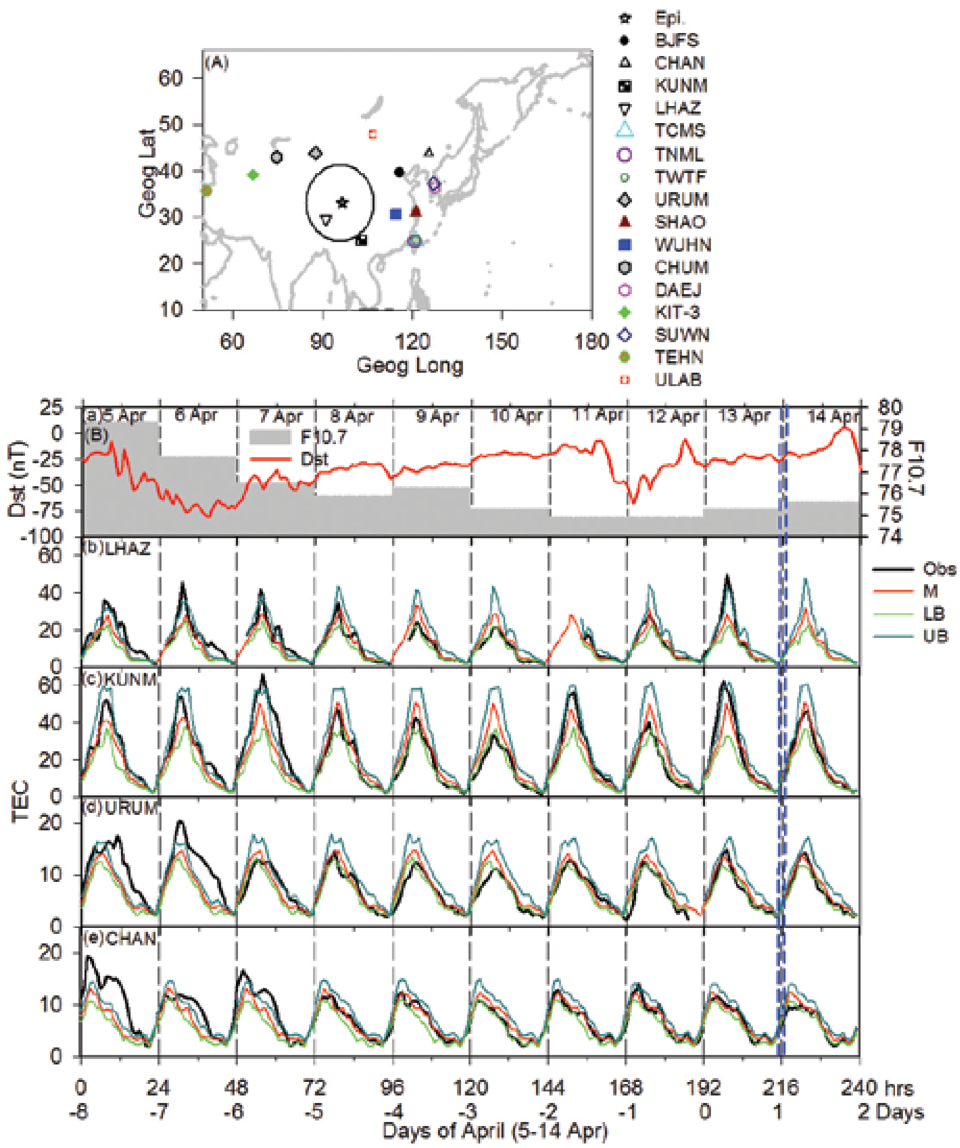

Figure 1. Upper panel (A): Represents the locations of the epicenter (star) with 16-IGS stations (symbols) considered in the study. Circle shows the preparatory zone of EQ (~ 930 km radius). Lower Panel (B): Variability of various parameters during 5-14 Apr 2010 with time: (a) Dst and F10.7 and obs TEC (Obs), Median (M), lower bound (LB) and upper bound (UB) over (b) LHAZ, (c) KUNM, (d) URUM and (e) CHAN respectively. The vertical line shows the occurrence time and day of EQ and its after shock.

To investigate the anomalies in the ionospheric behavior, which may have occurred during the earthquake, we examined the diurnal variability of observed TEC (Obs TEC), median (M), LB and UB (Figure 1(B)) as described in the 'data set and analysis' section. The TEC comprises electron densities in the D, E and F layer of the ionosphere with main contribution from F-layer. The well known diurnal pattern of TEC exhibits a steady increase during early morning when the photoelectron production begins and is maximum during noon time and then decreases due to the competitive effects of absence of photo-ionization and recombination of electrons with neutrals and ions during nighttime. It is well known that in the F region, the production rate of electrons depends on the atomic oxygen concentration [O], whereas the loss rate depends mainly on the molecular nitrogen concentration [N_2] with some contribution from the molecular oxygen [O_2]. We found from different stations that the observed TEC is minimum (≤ 5 TECU) through-out the nighttime at all stations and start increasing early in the morning. The rate of increase of TEC and the magnitude of noon-time TEC is higher over the low-latitude (≤ 30 deg) stations

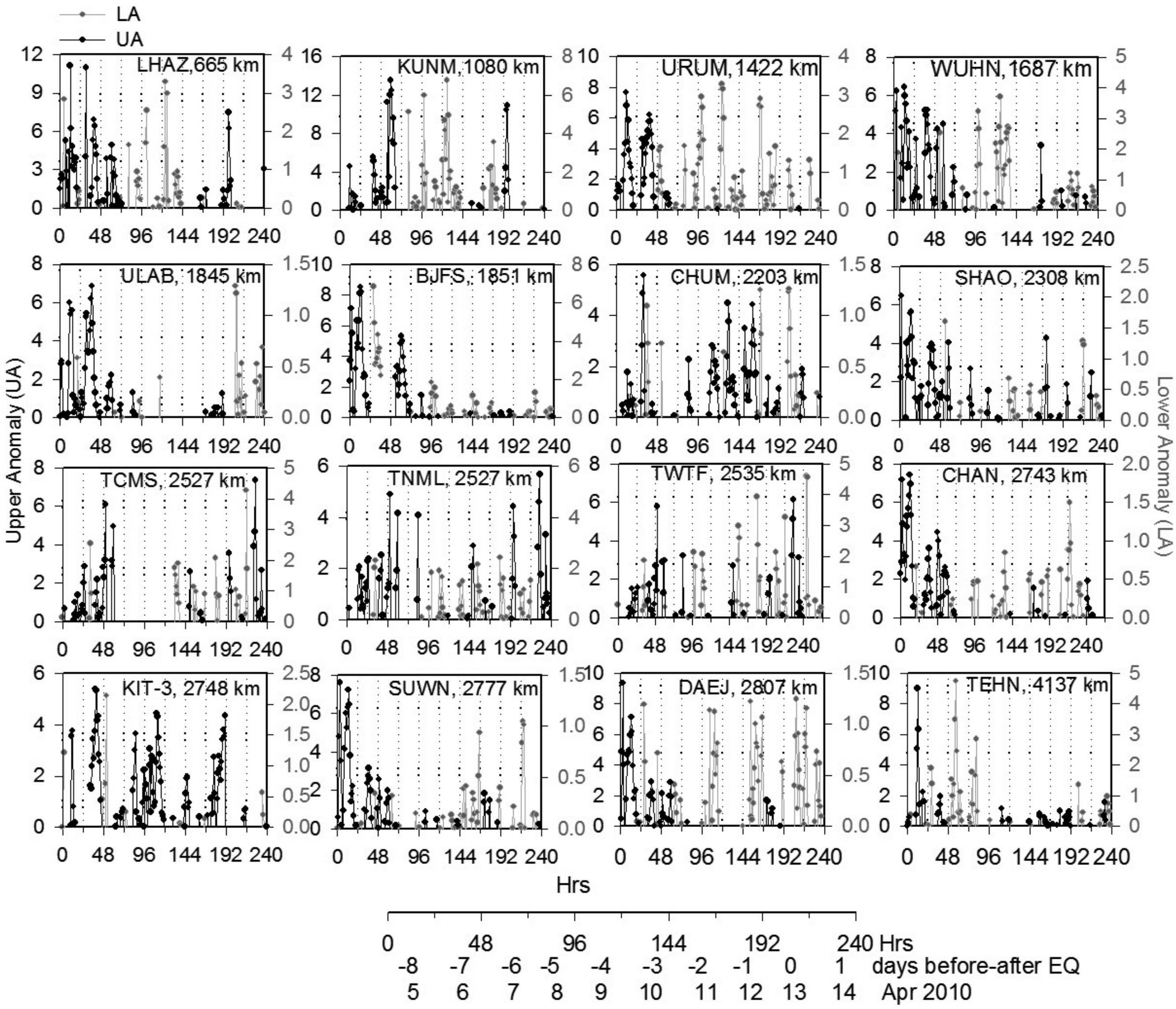

Figure 2. Represents the quantitative hourly anomalies in the upper bound (ObsTEC-UB, upper anomaly, UA, left-axis) and lower bound (LB-ObsTEC, lower anomaly, LA, right-axis) respectively over all 16-IGS stations during 5-14 April. The stations are arranged with the increase in the distance from the epicenter mentioned in each panel.

(LHAZ, KUNM, TCMS, TNML, TWTF), whereas at other higher mid-latitude stations (URUM, WUHN, BJFS, SHAO, CHAN, CHUM, KIT-3, ULAB, TEHN, SUWN and DAEJ) the response is weaker, showing a latitudinal response of production processes of electrons in the ionosphere.

The hourly anomalies in both the upper bound (ObsTEC-UB, UA) and lower bound (LB-ObsTEC, LA) over each station is examined and is presented in **Figure. 2**. The stations in **Figure 2** are arranged with the increase in the distance from the epicenter ,which is obtained by using the Haversine formula. The positive values of UA/LA indicate an enhancement/depletion of obs TEC from the UB/LB, respectively. When consecutively more than one third of hourly values (>7) of obs TEC in a day are higher or lesser than the upper and lower bounds of that particular day, we called that as an anomalous day. The higher anomalous TEC is observed during 5-7 Apr over all stations. Another increase in TEC is observed on 13 Apr (also an EQ day) over all the stations but the magnitudes are different, being higher at lower-latitude stations than over mid-latitude stations, which may again be attributed to the moderate storm period (Dst ~ -67 nT) of 12 Apr in the background. The ionospheric effect of a geomagnetic storm is considered a global phenomenon ,whereas EQ is a local phenomenon

(*Pulinets, 1998*). Considering this, we have looked into the ionospheric variabilities above the available stations, which are near-by and away from the epicentre. We found the method developed by *Liu et al., 2009* ,a robust method to remove the anomalous changes in hourly values. The storm time behavior is also distinct. During geomagnetic storms, strong electric fields and currents are transmitted between the magnetosphere and the high-latitude ionosphere, producing enhanced Joule heating and auroral particle precipitation in the auroral region. The conductivity of the ionosphere increases, neutral winds are accelerated, the thermosphere is heated up and the composition gets altered, and ionospheric plasma convection gets intensified and highly distorted. The perturbed neutral winds and composition propagates equator ward ,creating ionospheric and thermospheric disturbances over the entire globe (e.g., *Prolss, 1995; Aggarwal et al., 2013*).

From the lower panels of **Figure 1(B) and 2**, it is clear that on some days the Obs TEC lies between LQ and UQ, whereas on other days it is either higher or lower than UQ or LQ, respectively. Here mainly the days 5, 6, 7, 10 and 13 Apr exhibit the anomalous features. As said before also 5-7 and 12-13 Apr are disturbed periods when the TEC gets enhanced. But, it was not for a longer period (<7 hours). Whereas, on 10 Apr, the Obs TEC is close to LQ, which is even slighty lower than LQ for 7-10 hours. This anomalous decrease in Obs TEC is observed over LHAZ, KUNM, URUM and WUHN, whereas not over the stations far-away from the epicenter.

We can conclude from **Figure 2** that 6-8 days before the EQ, the TEC has enhanced on few days (UA) ,which has contributed to the high solar activity and disturbed period, as discussed earlier. And the anomalous depletions in TEC (LA) are observed 3-4 days (on 10 Apr) before the EQ in the ionosphere over nearby stations: LHAZ, KUNM, URUM and WUHN consecutively for ~7-10 hrs. Now, the question comes that how the variability in the plasma (electrons, TEC) may occur in the ionosphere few days before the earthquake. Although, the exact mechanism of the lithosphere-ionosphere coupling is still not known, possible explanations have been advanced by many workers in terms of E x B drift mechanism where the electric field (E) triggered by an earthquake preparatory process penetrates the ionosphere and, in the presence of local magnetic field (B), causes upward or downward movement of the ionization depending upon the direction of the electric field (Devi et al., 2008). The radon element, which is also a radioactive material is considered a source of ionization for the electric field generation mechanism. During the EQ, each α-particle emitted by ^{222}Rn (5.46 MeV) and its progeny, ^{218} Po (6 MeV) can produce ~10^5 ion-electron pairs. The heat released during the EQ depends on the number of H_2O molecules attached to the ion (*Pulinets and Ouzounov, 2011*). According to *Pulinets et al., (2006)*, the ion concentration increases in the area of the EQ preparation to ~10^5-10^6 cm^{-3}, which essentially changes the electric properties of the near ground layer of the atmosphere. The consequence of this process is the change in the air conductivity, which creates the possibility of the anomalous electric field generation. As a result of the local changes in the atmosphere electricity, the local changes of the electron concentration variability are induced in the ionosphere, which can be registered by different ionospheric techniques. From our observations, we found that spatial distribution of the anomalies was very local, which probably indicates association with seismo-ionospheric coupling processes. Some more detail investigations are needed to obtain quantitatively the changes in the other plasma and neutral parameters in the ionosphere to understand the seismo-ionosphere coupling.

ACKNOWLEDGEMENT

MA is grateful to the Department of Science and Technology (DST), India for awarding the Ramanujan Fellowship to carry out the work. She is also grateful to Prof. D.S Ramesh, Director of IIG, Mumbai for providing the hosting facilities at the Institute. The GPS data collected from various IGS stations, OMNI website and the USGS community are also highly acknowledged for making the data available. We are also grateful to the reviewers for their fruitful comments and suggestions.

REFERENCES:

Afraimovich, E. L., Astafyeva, E. I., 2008. TEC anomalies Local TEC changes prior to earthquakes or TEC response to solar and geomagnetic activity changes? Earth, Planets and Space, 60, 961-966.

Aggarwal, M., Joshi, H. P., Iyer, K. N., Kwak, Y.-S., Lee, J. J., Chandra, H., Cho, K. S, 2012. Day-to-day variability of equatorial anomaly in GPS-TEC during low solar activity period, Adv. Space Res., 49, 12, 1709-1720.

Aggarwal, M., Joshi, H. P., Iyer, K. N., Kwak, Y. S., 2013. Response of the EIA ionosphere to the 7-8 May 2005 geomagnetic storm. Adv. Space Res. 52, 4, 591-603.

Allen, J., 2010. The Galaxy 15 Anomaly: Another satellite in the wrong place at a critical time. Space Weather, 8, S06008, doi:10.1029/2010SW000588.

Astafyeva, E., Heki, K., 2011. Vertical TEC over seismically active region during low solar activity. J. Atmos. & Sol. Terr. Phys. 73, 13, 1643-1652.

Devi, M., Barbara, A. K., Depueva, A., Depuev, V., 2008. Preliminary results of TEC measurements in Guwahati, India. Adv. Space Res. 42, 753–756.

Dobrovolsky, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the size of earthquake preparation zones. Pure Appl. Geophys. 117, 1025–1044.

Kakinami, Y., Chen,C.H., Liu,J.Y., Oyama,K.-I., Yang,W.H., Abe,S., 2009. Empirical models of total electron content based on functional fitting over Taiwan during geomagnetic quiet condition. Ann.Geophys.27, 3321–3333.

Kinrade, J., Mitchell, C. N., Yin, P., Smith, N., Jarvis, M. J., Maxfield, D. J., Rose, M. C., Bust, G. S., Weatherwax, A. T., 2012. Ionospheric scintillation over Antarctica during the storm of 5-6 April 2010, J Geophys. Res., 117, A5, CiteID A05304.

Klobuchar, J., 1986. Design and characteristics of the GPS ionospheric time-delay algorithm for single frequency users, in: Proceedings of PLANS'86 – Position Location and Navigation Symposium, Las Vegas, Nevada, 4–7 November, pp. 280–286,

Klotz, S., Johnson, N.L. (Eds.), 1983. Encyclopedia of Statistical Sciences. John Wiley and Sons.

Le, H., Liu, L., Liu, J.Y., Zhao, B., Chen, Y., Wan, W., 2013. The ionospheric anomalies prior to the M9.0 Tohoku-Oki earthquake // Journal of Asian Earth Sciences, 62, 476-484.

Liu, J.Y., Chen, Y.I., Chen, C.H., Liu, C.Y., Chen, C.Y., Nishihashi, M., Li, J.Z., Xia, Y.Q., Oyama, K.I., Hattori, K., Lin, C.H., 2009. Seismoionospheric GPS total electron content anomalies observed before the 12 May 2008 Mw7.9 Wenchuan earthquake. J. Geophys. Res. 114, A04320, doi:10.1029/2008JA013698

Möstl, C., Temmer, M., Rollett, T., Farrugia,C. J., Liu, Y., Veronig, A. M., Leitner,M., Galvin, A. B., Biernat, H. K., 2010. STEREO and Wind observations of a fast ICME flank triggering a prolonged geomagnetic storm on 5–7 April 2010. Gophys. Res. Lett, 37, L24103, doi:10.1029/2010GL045175, 2010

Prikryl, P., Spogli, L., Jayachandran, P. T., Kinrade, J., Mitchell, C. N., Ning, B., Li, G., Cilliers, P. J., Terkildsen, M. , Danskin, D. W., Spanswick, E., Donovan, E., Weatherwax, A. T., Bristow, W. A., Alfonsi, L., De Franceschi, G., Romano, V., Ngwira, C. M., Opperman, B. D. L., 2011. Interhemispheric comparison of GPS phase scintillation at high latitudes during the magnetic-cloud-induced geomagnetic storm of 5–7 April 2010, Ann. Geophys., 29, 2287–2304, doi:10.5194/angeo-29-2287-2304.

Prolss, G.W. 1995. Ionospheric F region storms. H. Volland (Ed.), Handbook of Atmospheric Electrodynamics, CRC Press, Boca Raton, pp. 195–248.

Pulinets S.A., 1998. Seismic activity as a source of ionospheric variability. Adv Space Res. 22, 903-906.

Pulinets S. A. and Boyarchuk, K.A. 2004. Ionospheric precursors of earthquakes (Springer, Berlin, Germany).

Pulinets, S. A., Ouzounov, D., Ciraolo, L., Singh, R., Cervone, G., Leyva, A., Dunajecka, M., Karelin, A. V., Boyarchuk, K. A., Kotsarenko, A. 2006. Thermal, atmospheric and ionospheric anomalies around the time of the Colima M7.8 earthquake of 21 January 2003. Ann. Geophys., 24, 835–849.

Pulinets, S., Ouzounov, D. 2011. Lithosphere–Atmosphere–Ionosphere Coupling (LAIC) model – An unified concept for earthquake precursors validation. J. of Asian Earth Sciences, 41, 371–382.

Pundhir, D., Singh, B., Singh, O. P., 2014. Anomalous TEC variations associated with the strong Pakistan-Iran border region earthquake of 16 Apr 2013 at a low latitude station Agra, India. Adv. in Space Res. 53, 2, 226-232.

Smirnov, S. 2014. Reaction of electric and meteorological states of the near-ground atmosphere during a geomagnetic storm on 5 April 2010 // Earth, Planets and Space, 66: 154.

Watada, S. 2009. Radiation of acoustic and gravity waves and propagation of boundary waves in the stratified fluid from a time-varying bottom boundary, J. Fluid Mech., 627, 361–377, doi:10.1017/S0022112009005953.