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Anomalous variation in GPS based Total Electron Content (TEC), prior to six (6) earthquakes in 2016

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सार – इस अध्ययन में न्यूज़ीलैंड, ऑस्ट्रेलिया, सोलोमन द्वीप, निकारागुआ, इंडोनेशिया और पापुआ न्यू गुइनी में आए छह भूकंपों के जी पी एस (GPS) आधारित टी ई सी (TEC) डेटा का विश्लेषण किया गया है। ये भूकंप वर्ष 2016 के दौरान दुनिया भर में भिन्न-भिन्न अंतराल पर अलग-अलग स्थानों पर आए हैं। इस अध्ययन में उपयोग किए गए टी ई सी (TEC) डेटा को आई जी एस (IGS) स्टेशनों से रिनेक्स (RINEX) फॉर्मेट में प्राप्त किया गया है। उच्चतम टी ई सी (TEC) डेटा में वृद्धि भूकंप आने से 1-30 दिन पहले देखी गई है।

ABSTRACT. The present study reports the analysis of GPS based TEC for six earthquakes at New Zealand, Australia, Solomon Island, Nicaragua, Indonesia and Papua New Guinea. The considered earthquakes are at different intervals of time and different locations across the globe during the year 2016. The TEC data used in the study are obtained from IGS stations in RINEX format. Enhancement in peak TEC data are found 1-30 days prior to the earthquake.

Key words – GPS, TEC, IGS, RINEX, DST, Solar flux, Earthquake.

1. Introduction

The ionosphere of the Earth is a significant part of the global electric circuit. It is a subject to study disturbances related mainly with geomagnetic and solar activity. It also varies with different processes like, dust storms, radioactive pollutions, earthquakes, volcanic eruptions, thunderstorms, etc. The Earth's upper atmosphere absorbs solar radiation, which results in ionosphere heating, dissociation and ionization. Therefore, the total electron content (TEC) of the ionosphere is mainly controlled by the intensities of solar electromagnetic radiation. In periods of increasing solar activity, solar radiation variations over the short timescale (e.g., months, seasons) are intensive, rapid and nonlinear. For ionospheric data analysis, the solar radiation background in a signal is just like noise, which often increases difficulties in further processing, as the background always blurs the analytical signal. It is difficult or even impossible to analyze a signal with a strong background. To monitor simultaneously a large area of the ionosphere, the GPS is an ideal Tool. The GPS system consists of 24 satellites, evenly distributed in six orbital planes around the globe. Each satellite transmits two frequencies of signals f_1 = 1575.42 MHz and f_2 = 1227.60 MHz. The total electron content (TEC) is the total number of electrons along the vertical path between the satellite and the ground in 1 m^2 cross section column; TEC is measured in TEC units (1 TECU = 10^{16} el/m^2). Many researchers have reported that large seismic activities can be revealed through the unexpected variation in GPS based TEC of ionosphere (Parrot, 1995; Hayakawa and Molchanov, 2002; Pulinets *et al*., 2003; Pulinets and Ouznov, 2006; Afraimovich *et al.*, 2004; Liu *et al*., 2004; Karia and Pathak, 2011; Kim *et al*., 2012; Yadav *et al*., 2016).

Pulinets *et al*. (2007) have proposed the structure of Lithosphere-Atmosphere- Ionosphere Coupling model (LAIC) which permitted a common conception of different kinds of specific variations of geochemical, atmospheric, electromagnetic and ionospheric parameters observed before strong earthquakes. They add that air ionization by radon takes place over the large territories and has a strong effect on the following processes in the atmospheric boundary layer: (*i*) formation of the large ion clusters due to water molecules attachment to ions; (*ii*) latent heat release; (*iii*) changing of boundary layer electric conductivity; (*iv*) upward convective flux, generation of anomalous electric field; (*v*) air temperature

TABLE 1

Details of earthquake and IGS station

S. No.	Epicentre and magnitude of earthquake	Date	Location of IGS Station
1.	Gisborne, New Zealand (37.35 S, 179.14 E) M-7.0	1 Sep 2016	Wellington, WGTN (41.32 S, 174.80 E)
2.	Macquarie Island, Australia (54.6136 S, 158.71 E) M-6.1	8 Sep 2016	Macquarie Island, MAC1 (54.99 S, 158.54 E)
3.	Auki, Solomon Islands (8.67 S, 160.55 E) M-6.2	10 Jun 2016	Solomon Islands, SOLO (9.43 S, 159.95 E)
4.	Puerto Morazan, Nicaragua (12.83 N, 86.96 W) M-6.1	10 Jun 2016	Managua, Nicaragua, MANA (12.14 N, 86.24 W)
5.	Pamanukan, Indonesia (4.8626 S, 108.1627 E) M 6.5	19 Oct 2016	Cibinong, BAKO (6.4900 S, 106.8500 E)
6.	Kandrian, Papua New Guinea (6.0033 S, 148.8830 E) M 6.3	17 Oct 2016	Papua New Guinea LAE1 (6.6733 S, 146.9920E)

TABLE 2

Summary of the data and results obtained for all the earthquakes considered

S. No.	Epicentre and magnitude of earthquake	Date	Enhancement in TEC prior to EQ
1.	Gisborne, New Zealand (37.35 S, 179.14 E) M-7.0	1 Sep 2016	1, 24 and 28 days (Fig. 1)
2.	Macquarie Island, Australia (54.6136 S, 158.71 E) M-6.1	8 Sep 2016	4,5 and 24 days (Fig. 2)
3.	Auki, Solomon Islands (8.67 S, 160.55 E) M-6.2	10 Jun 2016	4,18, 19,20 and 24 days (Fig. 3)
4.	Puerto Morazan, Nicaragua (12.83 N, 86.96 W) M-6.1	10 Jun 2016	18, 20, 23 and 24 days (Fig.4)
5.	Pamanukan, Indonesia (4.8626 S, 108.1627 E M-6.5	19 Oct 2016	8, 11, 16 , 17, 20 ,21 and 24 days (Fig. 5)
6.	Kandrian, Papua New Guinea (6.0033 S, 148.8830 E) M-6.8	17 Oct 2016	6,9, 10 , 14 , 15 ,18, 19 and 21 (Fig. 6)

increase and drop of relative humidity and (*vi*) specific shape clouds formation. Variations of atmospheric electricity stimulated by the ionization process induce variations in the ionosphere through the global electric circuit. The simultaneous co-existence of several processes manifesting this coupling explains the variety of observed phenomena and enhances the reliability of detecting the future seismogenic signals. Hence these phenomena contribute the effect on TEC of upper atmosphere. One more hypothesis has been proposed by Hayakawa (2004). They suggested the mechanism of coupling between the lithospheric activity and ionosphere to be distributed in three channels, first chemical channel; second acoustic channel and third electromagnetic channel. As for the chemical channel, the geochemical quantities (such as surface temperature, radon emanation etc.) induce the perturbation in the conductivity of the atmosphere leading to the ionospheric modification through the atmospheric electric field.

The present paper reports the analysis of GPS based TEC for six earthquakes at New Zealand, Australia, Solomon Island, Nicaragua, Indonesia and Papua New Guinea. The selected IGS stations have been selected within the range of 200 km from the epicentre location.

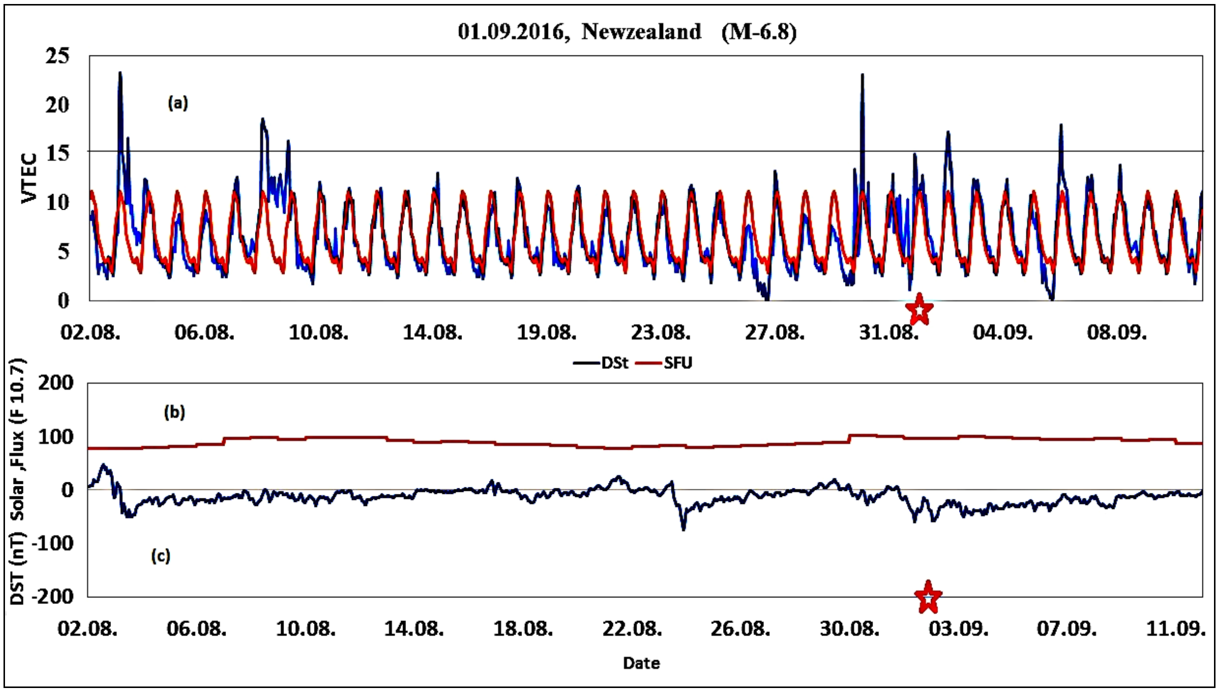
2. Data analysis

2.1. *Earthquake data*

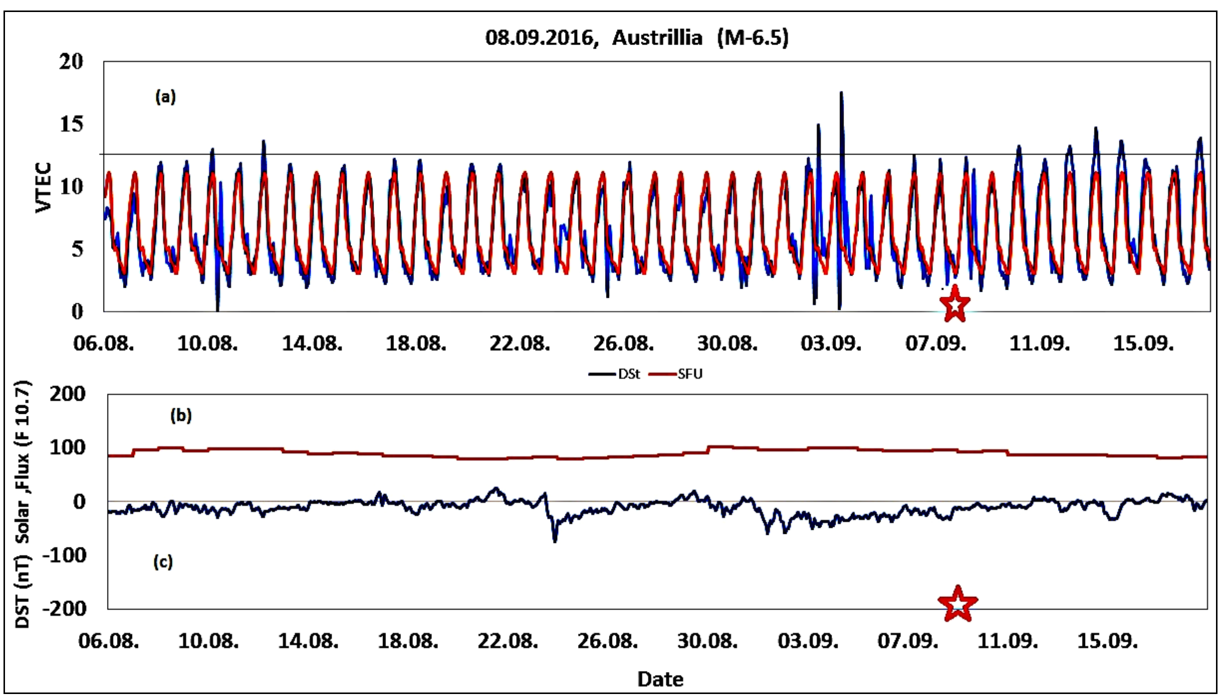
During the past decade, dozens of disastrous earthquakes occurred in close proximity to an ocean or below the seafloor. In this paper, we consider six earthquakes at New Zealand, Australia, Solomon Island, Nicaragua, Indonesia and Papua New Guinea. The main selection criteria include a magnitude of M > 6.0 and near or beneath an ocean. Table 1 gives the epicentral locations and details of IGS Stations of the selected Earthquakes, (http://earthquake.usgs.gov/).

2.2. *TEC data*

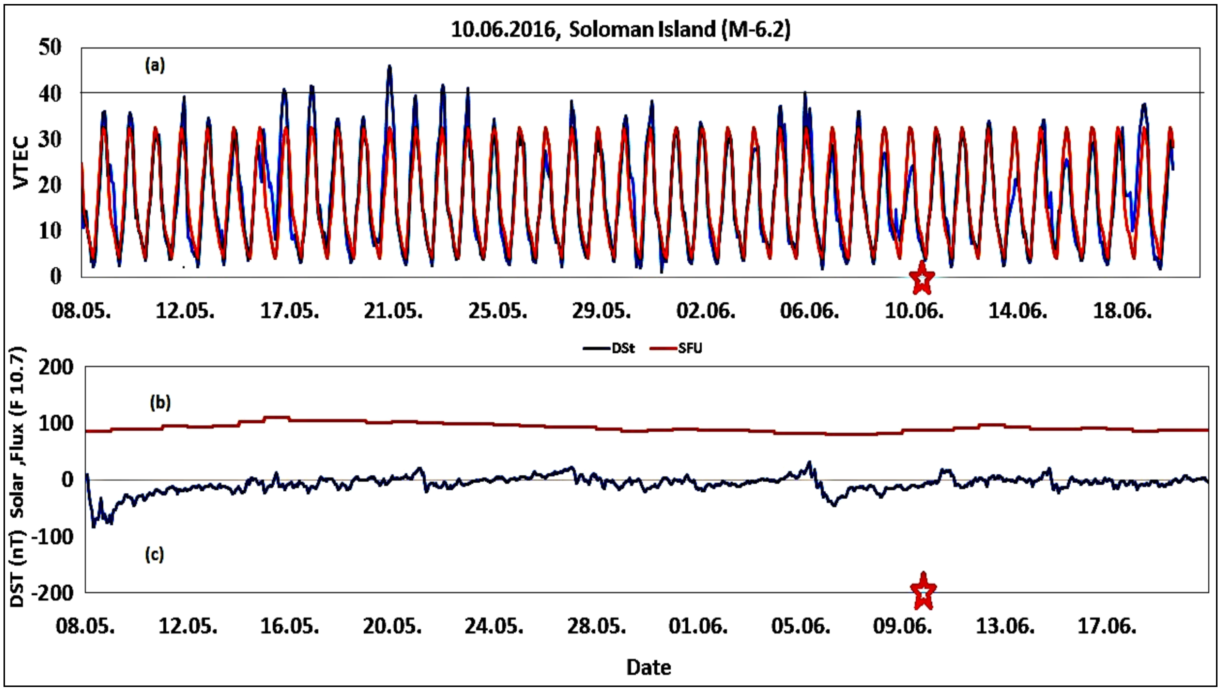
The RI NEX data obtained from GPS receivers, contain the C1 (C/A code pseudo range, in meters, on L1



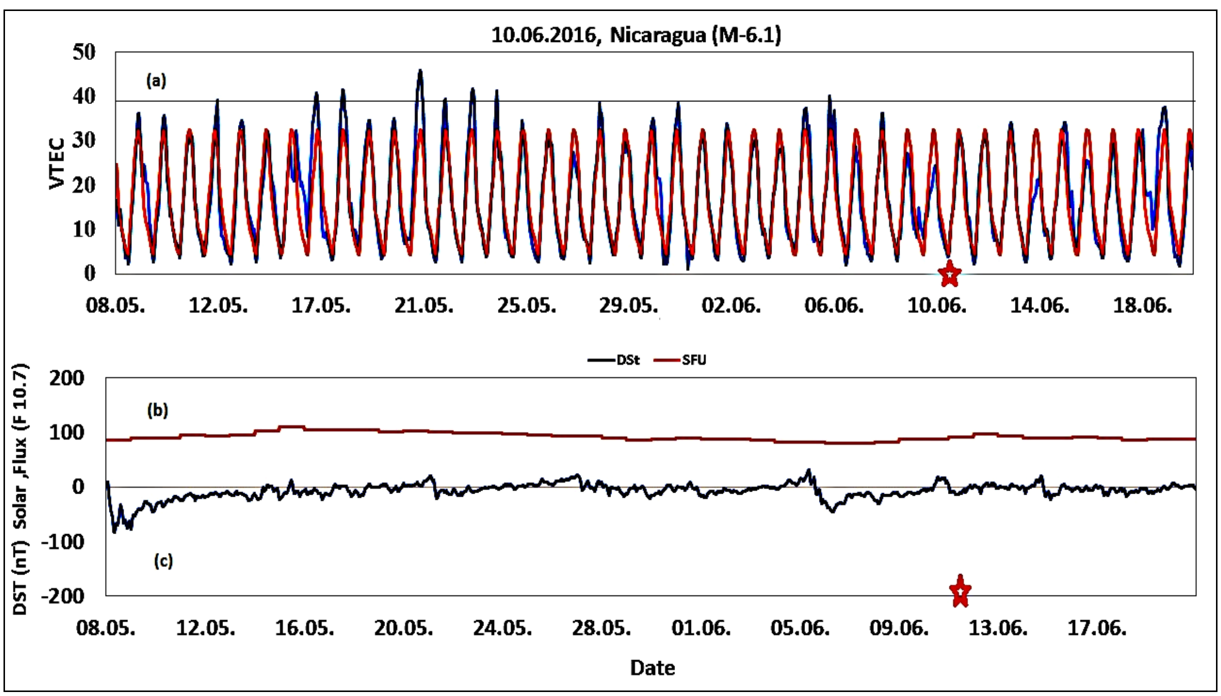
Figs. 1(a-c). VTEC profile of the Wellington, WGTN station; VTEC diurnal profile indicates an enhancement in diurnal VTEC (blue line) prior to the earthquake; the star symbol represents the earthquake day. (b) Variation in DST index. The geomagnetic condition is found to be quiet with small variation in DST index. (c) Variation in solar F-10.7 cm. No major variation is seen



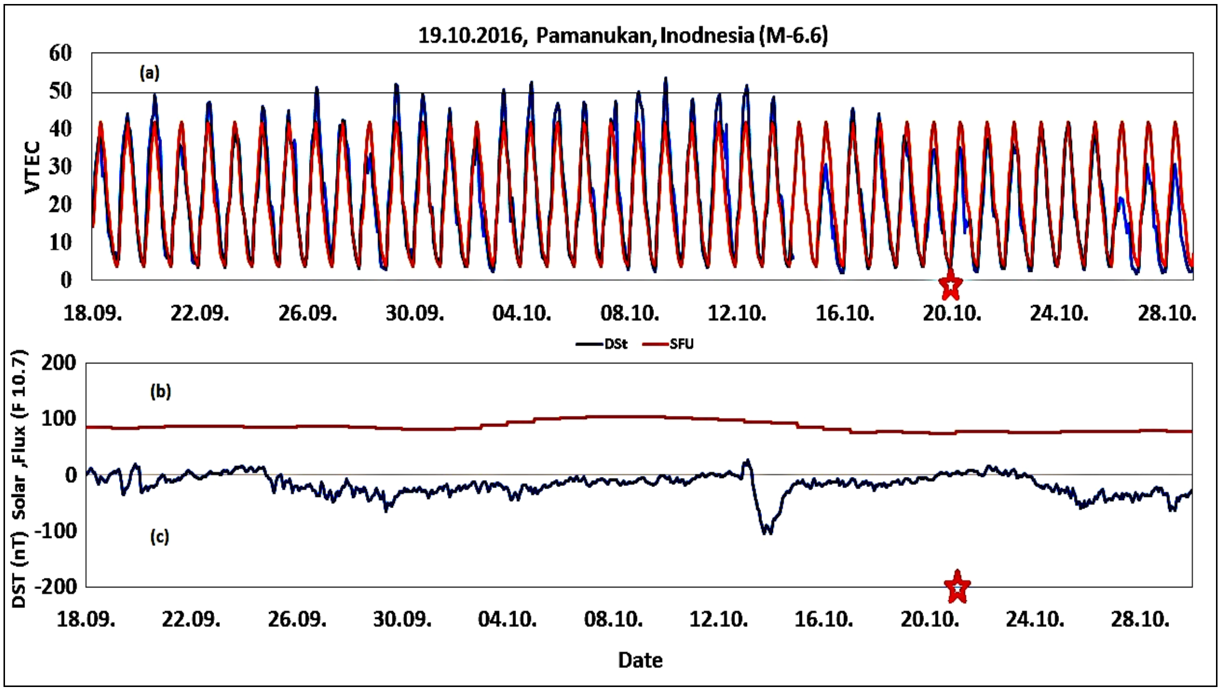
Figs. 2(a-c). VTEC profile of the Macquarie Island, Australia MAC1 station; VTEC diurnal profile indicates an enhancement in diurnal VTEC (blue line) prior to the earthquake the star symbol represents the earthquake day. (b) The variation in DST index. The geomagnetic condition is found to be quiet with small variation in DST index. (c) Variation of solar F-10.7 cm. No major variation is seen



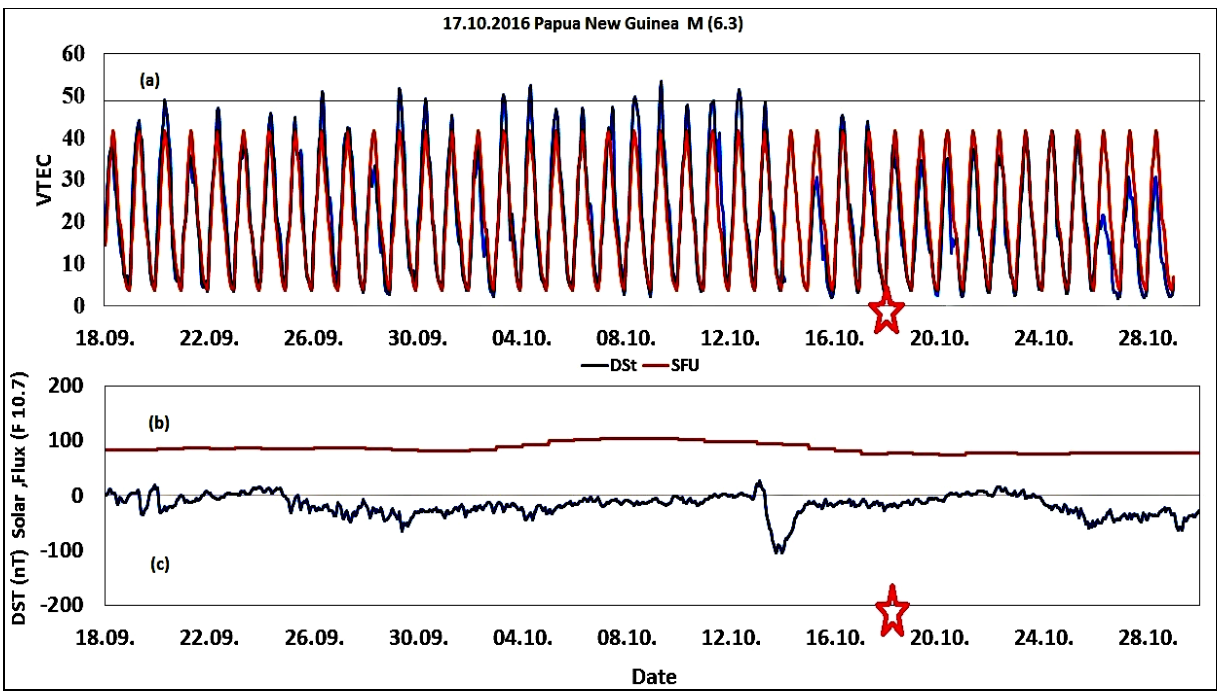
Figs. 3(a-c). VTEC profile of the Solomon Islands SOLO station; VTEC diurnal profile indicates an enhancement in diurnal VTEC (blue line) prior to the earthquake. The star symbol represents the earthquake day (b) The variation of DST index. The geomagnetic condition is found to be quiet with small variation in DST index.(c) The variation of solar F-10.7 cm. No major variation is seen



Figs. 4(a-c). VTEC profile of the Managua, Nicaragua MANA station; VTEC diurnal profile indicates an enhancement in diurnal VTEC (blue line) prior to the earthquake. The star symbol represents the earthquake day. (b) The variation displays DST index, the geomagnetic condition is found to quiet with small variation in DST index. (c) The variation in solar F-10.7 cm. No major variation is seen



Figs. 5(a-c). VTEC profile of the Cibinong, BAKO station; VTEC diurnal profile indicates an enhancement in diurnal VTEC (blue line) prior to the earthquake, the star symbol represents the earthquake day. (b) The variation displays DST index. The geomagnetic condition is found to quiet with small variation in DST index. (c) The variation in solar F-10.7 cm. No major variation is seen



Figs. 6(a-c). VTEC profile of the Papua New Guinea LAE1 station; VTEC diurnal profile indicates an enhancement in diurnal VTEC (blue line) prior to the earthquake. The star symbol represents the earthquake day. (b) The variation displays DST- index. The geomagnetic condition is found to quiet with small variation in DST index. (c) The variation of solar F-10.7 cm. No major variation is seen frequency), P2 (P code pseudo range, in meters, on L2 frequency), L1 (L1 carrier phase, in cycles, on L1 frequency) and L2 (L2 carrier phase, in cycles, on L2 frequency) with a time resolution of 30s.

The Slant Total Electron Content (STEC) estimated, from an IGS data set of RINEX format, as,

$$\text{STEC} = \left(\frac{f_1^2 \, f_2^2}{f_1^2 - f_2^2} \right) \frac{\left(p_1 - p_2 \right)}{40.3} \qquad (1)$$

where, f_1 (1227.60 MHz) and f_2 (1575.42 MHz) are current GPS broadcast frequencies.

STEC converted into Vertical Total Electron Content (VTEC) using a suitable mapping function of different Ionosphere Pierce Point (IPP) locations. The mapping function S (E) is defined as,

$$\text{S (E)} = (\text{Cos}\chi'), \qquad (2)$$

$$\text{VTEC} = \text{STEC/S (E)}, \qquad (3)$$

where,

$$Cos\,\chi' = \sqrt{1 - \left(\frac{R_x \, Cos\,\chi^2}{R_x \, h_m} \right)} \qquad (4)$$

Rx = mean earth radius, 6371 km, χ = elevation angle and χ' is zenith angle and h_m = altitude of the IPP = 350 km, is the height of the ionospheric shell above the earth's surface (Rama Rao *et al*., 2006a).

The mean ionospheric height of 350 km is used for the determination of IPP locations, which is found to be valid for elevation greater than 50º. All TEC values for elevation lower than 50º are removed to eliminate the low elevation angle effects (such as, multipath and tropospheric scattering on the measured TEC values) (Rama Rao *et al*., 2006b; Karia and Pathak, 2011).

The solar F10.7 cm data have been obtained from the National Oceanic and Atmospheric Administration (NOAA) data centre.

The analysis of each earthquake under study is presented in a plot in three sections; the plot presents: (a) VTEC profiles for a period of 40 days, (b) Disturbance Storm Time (DST) index and (c) solar flux (F-10.7) variation of the analysed period with a purpose to refer to the geomagnetic and solar condition.

3. Results and discussion

The present paper pays attention to the variation of multi-sensor parameter of ionosphere anomalies prior to the earthquake using TEC in the detection of earthquake precursor. The result of enhancement in TEC, prior to all earthquakes is summarized in Table 2.

3.1. *TEC variation*

There is no common opinion among the scientists on the physical mechanism that could explain the seismo-ionosphere coupling.

Earthquake genesis is found to be very complicated and there are no common consensus among scientists to understand what causes the genesis of earthquakes (Mishra *et al*., 2008; Mishra, 2012; Mishra, 2014), which in turns suggest that increase of stress level within the causative source may lead to emanation of gases (e.g., Radon, Helium) from the crustal rocks that might have taken as the earthquake precursor but not indicating the exact processes involved in it (Mishra, 2012). This observation suggest that some other forces related to earth and atmospheric interactions could be one of the plausible reason for earthquake genesis.

It is still a subject of discussion and detailed review of the proposed physical mechanism may be found in Karia and Pathak (2011); Akhoondzadeh and Saradjian (2011) and Choi *et al*. (2012). Enhancement in TEC during and after the earthquake has been reported in Devi *et al*. (2004) and Karia and Pathak (2011). It was proposed by Parrot (1995) that propagation of the direct wave due to compression of rocks close to the earthquake epicentre could be more likely related to the piezoelectric and turboelectric effect. Rising liquids under the ground would lead to the emanation of warm gases, as proposed by Hayakawa and Molchanov (2002). Pulinets and Boyarchuk (2004) suggested an elaborate mechanism in which the radon emission ionizes the near-earth atmosphere over the seismic zone. Penetration of atmospheric gravity waves (AGW), which are driven by the gas water release from the earthquake preparatory zone into the ionosphere, was suggested by Hayakawa and Molchanov (2002). Convective transportation of charged aerosols and their gravitational sedimentation in the atmosphere as well as radon and their radioactive element emanation in to lower atmosphere over the faults leads to increase of the atmospheric radioactivity level during earthquake formation. These processes may lead to an increase in the electric field up to ten mV/m in the ionosphere (Sorokin *et al*., 2007; Chmyrev *et al*., 1989). It is possible that pre-seismic vertical electric field on the ground surface, transformed into an electric field perpendicular to geomagnetic field line, produces a perturbation over the F-region ionosphere. Once the F-region gets perturbed within that zone, it will pre-start to propagate along the conducting magnetic field lines and spread over wider areas, as discussed by Liu *et al*. (2006) and Pulinets and Boyarchuk (2004).

In the present report, enhancement in peak TEC was observed beyond the standard deviation line (black line) prior to the earthquakes , New Zealand, Australia, Soloman Island, Nicaragua, Indonesia and Papua New Guinea (Figs. 1-6). There is an anomalous reduction in TEC values which can be explained as follows.

Depletion and enhancement in density profile may be the result of earthquake associated E × B drift when electron density may flow into or out of the observing station, depending upon the location of the station (Parrot and Mogilevsky, 1989). Devi *et al*. (2001) found that enhancement and depletion in TEC variations for a number of strong earthquake events indicate that high-density TEC contours are often associated with earthquakes having their epicenters near the equator or away from the observational site. They further indicated that TEC depletions are often observed when the epicenter lies very near to the observational site.

4. Summary

The present paper reports the variation in ionospheric parameter, TEC, prior to six different earthquakes that have occurred across the globe. The TEC anomaly is observed from 1 to 30 days prior to all six earthquakes.

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The contents and views expressed in this research paper/article are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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