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Yazar(lar) (Author(s)): *Mustafa ULUKAVAK, Mualla YALÇINKAYA, Muhammed Arslan TARİQ*

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6. Uluslararası GAP Mühendislik Kongresi

Investigation of the Possible GPS-TEC Anomalies before the 2005 Northern Peru Earthquake

Mustafa Ulukavak[1], Mualla Yalçınkaya[2], Muhammed Arslan Tariq[3]
[1]Harran University, Department of Geomatics Engineering, Şanlıurfa, Turkey
[2]KaradenizTechnical University, Department of Geomatics Engineering, Trabzon, Turkey
[3]Centre for Earthquake Studies, National Centre for Physics, Islamabad, Pakistan
e-posta: mulukavak@harran.edu.tr

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Abstract

Recently, Total Electron Content (TEC) data, obtained from Global Navigation Satellites Systems (GNSS) receivers, are increasingly being used to detect seismo-ionospheric anomalies. In this study, Global Positioning System – Total Electron Content (GPS-TEC) data were used to investigate ionospheric abnormal behaviors prior to the 2005 Northern Peru earthquake (5.674 S, 76.409 W, September 26, 2005, 01:55:37 UT, Mw:7.5). The data obtained from three International GNSS Service (IGS) stations near the epicenter of the earthquake were used to detect ionospheric anomalies before the earthquake. Solar activity (F10.7), geomagnetic storm (Kp) and geomagnetic activity (Dst) index values which are both related to space weather conditions, were used to analyze these pre-earthquake ionospheric anomalies. Analysis results revealed that anomalies occurred and the possible ionospheric VTEC anomalies associated with the earthquake obtained four to nine days before the Northern Peru earthquake. This study is supported by TUBITAK, Environment, Atmosphere, Earth and Marine Science Research Support Group (CAYDAG) grant no. 116Y109.

Keywords: Ionosphere; Space Weather Conditions; VTEC; Earthquake; Northern Peru; GNSS

2005 Kuzey Peru Depremi Öncesinde Ortaya Çıkan Muhtemel GPS-TEC Anomalilerinin İncelenmesi

Özet

Son zamanlarda, Global Navigasyon Uydu Sistemleri (GNSS) alıcılarından elde edilen Toplam Elektron İçeriği (TEC) verileri, sismo-iyonosferik anomalileri tespit etmek için giderek daha fazla kullanılmaktadır. Bu çalışmada, 2005 Kuzey Peru depremi öncesinde iyonosferik anormal davranışları araştırmak için Küresel Konumlandırma Sistemi- Toplam Elektron İçeriği (GPS-TEC) verileri kullanılmıştır (5.674 G, 76.409 B, 26 Eylül 2005, 01:55:37 UT, Mw:7.5). Deprem merkez üssüne yakın üç Uluslararası GNSS Servisi (IGS) istasyonundan elde edilen veriler deprem öncesi iyonosferik anomalileri tespit etmek için kullanılmıştır. Deprem öncesi iyonosferik anomalileri incelemek için, uzay iklim koşullarına bağlı güneş aktivitesi (F10.7), jeomanyetik fırtına (Kp) ve jeomanyetik aktivite (Dst) indis değerleri kullanılmıştır. Analiz sonuçlarına bakıldığında, anomalilerin ortaya çıktığı ve depremle ilişkili muhtemel iyonosferik VTEC anomalilerinin, Kuzey Peru depreminden dört ila dokuz gün önce meydana geldiği görülmüştür. Bu çalışma TÜBİTAK, Çevre, Atmosfer, Yer ve Deniz Bilimleri Araştırma Destek Grubu (CAYDAG) tarafından 116Y109 nolu proje ile desteklenmektedir.

Anahtar kelimeler: İyonosfer; Uzay İklim Koşulları; VTEC; Deprem; Kuzey Peru; GNSS

1. Introduction

Data obtained from dual-frequency GNSS receivers have recently been used both for ionospheric studies and for accurate positioning. Dual-frequency GNSS receivers are used to derive TEC data, which provide users with more information on the upper atmosphere. The great Alaska earthquake in 1964 was the first earthquake whose seismic-ionospheric anomalies were investigated [7, 18]. Earthquake precursors have been a research interest for a significant number of scientists. The relationship between seismic events and unforeseen variations in ionospheric activity has been the main topic of several studies [1, 21, 28, 29].

Satellite- and ground-based instruments have been used to examine seismo-ionospheric effects. Several hypothesis on the seismic and electromagnetic mechanism of geochemical and geophysical process have also been explained by [25, 30, 32]. The ionospheric effects that relate to the Northridge earthquake were measured by [3] by using GPS-TEC data. They concluded that TEC variations were due to acoustic gravity waves. Pre-earthquake ionospheric anomalies have also been observed 15 days before and after some earthquakes [3]. [22] investigated the earthquakes that occurred in Taiwan from 1999 to 2002, with magnitudes greater than or equal to six. The ionospheric TEC decreased drastically one to five days prior to the earthquakes. [27] determined the GPS-TEC variations after the powerful earthquake that occurred in West Sumatra, Indonesia on December 26, 2004. They concluded that the TEC increased by 1.6 6.9 TEC units (TECU) north of the epicentre. [11] examined ionospheric perturbations prior to the earthquakes (of M≥7.0) in the Sumatra area by using GPS data and Challenging Minisatellite Payload data. They detected some positive and negative anomalies that range from a few hours to six days prior to the earthquakes. [16] investigated the ionospheric anomalies by using global ionosphere map (GIM) data obtained from the global ionosphere maps. Ionospheric anomalies before an earthquake have raised attention on the pre-earthquake ionospheric anomalies for special earthquake events [12, 14, 19, 20, 38, 40].

This paper investigated the ionosphere associated with seismic activity before the earthquake (September 26, 2005) in Northern Peru. This region has been studied previously by [39], who conducted analysis of ionospheric TEC anomalies before the 2005 Northern Peru earthquake. Their results showed the anomalies from 5 days to several hours prior to an earthquake. Their study used GIM-TEC (two-hour resolution) data and 20 days median analysis method, whereas, in the current study, we estimated GPS-TEC data (one-hour resolution) obtained from the GNSS stations and analysed with using 15-days moving median analysis method near the epicentre of the earthquake. The rest of the paper is organised as follows. Section 2 describes the method for estimating the GPS-TEC variations while Section 3 explains the methods of anomaly analysis. Section 4 explains the pre-earthquake ionospheric anomaly analysis of the 2005 Northern Peru earthquake and their space weather conditions. Section 5 presents the conclusions of the study.

2. Obtaining GPS-TEC Variations Using GPS Observations

Ionospheric TEC can be quantified either by using the geometry-free linear combination of the code (P) or by using carrier phase (Φ) measurements [36]. For pseudo-range measurements, the geometry-free linear combination can be calculated by subtracting the P_2 code measurements from the P_1 code measurements, is given as:

$$P_{4,u}^{m} = P_1 - P_2 = A\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) STEC_u^m + DCB^m + DCB_u \quad (1)$$

where f_1 and f_2 are the carrier frequencies of L1 and L2 signals of GPS satellites, respectively; $A = 40.3\, m^3/s^2$ and $STEC_u^m$ denotes the Slant Total Electron Content (STEC) in units of TECU ($1\ \mathrm{TECU} = 10^{16}\mathrm{electrons/m^2}$) on the slant signal path that combines the receiver u and the satellite m; and DCB^m and DCB_u are differential code biases (DCBs) of pseudo-range measurements defined for the satellite and the receiver, respectively. For carrier phase measurements, the geometry-free linear combination can be obtained by subtracting the Φ_2 phase observations from Φ_1 phase observations as follows:

$$\Phi_{4,u}^{m} = \Phi_1 - \Phi_2 = -A\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) STEC_u^m + IFB^m + IFB_u + \Delta N_{u,4}^m \quad (2)$$

where IFB^m and IFB_u are the inter-frequency biases for the carrier-phase measurements of the satellite and the receiver, respectively, the combined ambiguity term $\Delta N_{u,4}^m$ in Eq. (2) is defined as follows:

$$\Delta N_{u,4}^{m} = \lambda_1 \mathrm{N}_{u,1}^{m} - \lambda_2 \mathrm{N}_{u,2}^{m} \quad (3)$$

where, $\mathrm{N}_{u,1}^{m}$ and $\mathrm{N}_{u,2}^{m}$ denote the integer phase ambiguities, and λ_1, λ_2 are the wavelengths that correspond to f_1 and f_2 frequencies, respectively [8, 13].

DCBs should be determined to obtain unbiased STEC. DCBs are provided for some IGS stations for certain dates in the IONEX files, which are provided mostly by Jet Propulsion Laboratory (JPL), Center for Orbit Determination in Europe (CODE), and European Space Agency (ESA) Ionosphere Associate Analysis Centers. STEC can be computed by eliminating the DCBs from the geometry-free linear combination given in Eq. (1).

$$STEC_u^m(n) = \frac{1}{A}\left(\frac{f_1^2 f_2^2}{f_2^2 - f_1^2}\right)\left[P_{4,u}^m(n) - (DCB^m + DCB_u)\right] \qquad (4)$$

where the index n denotes the index of time sample ranging from 1 to N, which is the total number of time samples in a record. A typical GNSS receiver records data on every 30 seconds. For a continuous 24-hour period, the maximum value for N is 2880. If the DCB values for satellites and receiver are known, then the STEC can be computed for each arc by using Eq. (4). However, the noise level in P_4 measurements is higher than Φ_4. Thus Φ_4 data are usually fitted to P_4 to smooth the P_4 observations using the advantage of less noisy carrier-phase measurements. Several fitting algorithms have been proposed in the literature [13, 26]. Leveling or fitting of Φ_4 to P_4 is achieved by defining a constant offset for each continuous arc of phase measurement as follows:

$$B^m = \frac{1}{N_{me}}\sum_{n_{me}=1}^{N_{me}}\left(P_{4,u}^m(n_{me}) + \Phi_{4,u}^m(n_{me})\right) \qquad (5)$$

where B^m denotes the constant offset value for the m^{th} satellite, N_{me} is the total number of samples in each phase-continuous arc and n_{me} is the time duration of the total samples in each arc. Each cycle-slip or phase discontinuity starts another constant offset calculation. The constant offset value B^m is combined with Φ_4 in Eq. (6) to obtain the STEC as follows:

$$STEC_u^m(n) = \frac{1}{A}\left(\frac{f_1^2 f_2^2}{f_2^2 - f_1^2}\right)\left(B^m - \Phi_{4,u}^m(n) - (DCB^m + DCB_u)\right) \qquad (6)$$

VTEC can be obtained using a thin-shell approximation [15] of the single layer ionosphere model for which the relation between STEC and VTEC is given as follows:

$$M\left(z_m(n)\right) = \frac{STEC_u^m(n)}{VTEC_u^m(n)} \qquad (7)$$

where, $z_m(n)$ is the satellite zenith angle at the receiver position and the mapping function $M(z)$ is defined as follows:

$$M(z) = \frac{1}{\cos z'} = \frac{1}{\sqrt{1-\sin^2 z'}}\ , \quad \sin z' = \frac{R}{R+H}\sin(\alpha z) \qquad (8)$$

where z' is the zenith angle at the ionospheric pierce point (IPP) where the line-of-sight between the satellite and the ground receiver intersects the thin shell; R is the earth radius (6,378.137 km); $\alpha = 0.9886$ is a scaling factor of the modified single layer mapping function [35] and H is the ionospheric shell height (350 km) [4, 37].

The DCB values of the satellites and some other receivers are available from the final daily IGS IONEX files. The order of spherical harmonics expansion depends on the areas; for instance, 4th, 8th, and 15th order for the regional, continental, and global size, respectively [13]. The calibrated STEC variations are obtained by removing the estimated DCBs from each satellite arc in Eq. (6). The VTEC values are determined by employing Equation (7) for each satellite continuous arc.

In order to monitor anomalous days, the VTEC values at IPP points should be utilized to get daily VTEC variations over each ground station. In this study, the hourly VTEC values are estimated with the calibrated VTEC values at IPP over each GNSS station by fitting the approximation of second-order polynomial surfaces to IPP points for a 24-hour run [10].

$$VTEC(\varphi_{IPP}, s_{IPP}) = a_0 + a_1\varphi_{IPP} + a_2 s_{IPP} + a_3{\varphi_{IPP}}^2 + a_4\varphi_{IPP}s_{IPP} + a_5{s_{IPP}}^2 \qquad (9)$$

where, φ_{IPP} and s_{IPP} are the spherical coordinates of the IPP in a sun-fixed reference frame, and a_0, a_1, a_2, a_3, a_4 and a_5 are the polynomial surface coefficients. The hourly unknown polynomial surface coefficients are estimated using least-squares estimation in Eq. (9). For an hourly estimation of polynomial surface coefficients, the data window can be set to 120 epochs (60 epochs before and after each hour). The topside hourly VTEC values for each station are calculated by substituting the sun-fixed spherical coordinates of each station alongside the estimated polynomial surface coefficients in Eq. (9). Insufficient data will cause problems when estimating the hourly VTEC value. However, the missing VTEC values above the stations should also be completed by interpolating the grid TEC data obtained from IGS IONEX files [34].

3. Analysis of GPS-TEC Variations

Investigation on the pre-earthquake ionospheric VTEC anomalies can be performed by using 15-day moving median (MM) methods that employ the quartile-based statistical analysis method [23]. The MM values of GPS-TEC were calculated in advance by using the quartile-based statistical analysis method. The lower quartile (LQ) and upper quartile (UQ) were also calculated. If the GPS-TEC values are in the normal distribution with mean (m) and standard deviation (σ), the excepted values of MM and LQ or UQ are in m and 1.34σ, respectively [16]. The lower bound (LB) and upper bound (UB) are calculated as LB=MM-1.5(M-LQ) and UB=MM+1.5(UQ-M), respectively. Anomalous variation can be detected in observed GPS-TEC greater than UB or lesser than the associated LB [23]. For example, the VTEC values of the first 15 days were used to generate the MM, UB, and LB for the 16th day. Similarly, 15 days of VTEC data between the 2nd and 16th day were used to generate bounds for the 17th day. Determination of UB and LB continues in this manner until the end of the data. Each day is marked anomalous when more than one-third of data (e.g., eight hours are anomalous in a day) is greater or lesser than the upper and lower bounds.

4. Ionospheric TEC Precursors of the 2005 Northern Peru Earthquake

In this study, the 2005 Northern Peru earthquake (5.674°S, 76.409°W, September 26th, 2005, 01:55:37 UTC), with a magnitude of 7.5 earthquake was investigated (http:/earthquake.usgs.gov). In this study, GPS-TEC data were used to investigate ionospheric abnormal behaviors prior to the 2010 Baja California earthquake. All calculations and some statistical procedures were performed by MATLAB scripts. All maps and graphics were plotted in MATLAB.

For this earthquake, the radius of the earthquake preparation zone (EPZ) was estimated using the Dobrovolsky formula: $\rho = 10^{0.43*\mathrm{M}}$, where ρ is the radius of the EPZ (km) and M is the magnitude of the earthquake on the moment magnitude scale [9]. The radius of the EPZ for the 2005 Northern Peru earthquake was calculated to be 1678.80 km from the epicenter of the earthquake. IGS stations near the earthquake zone are AREQ, BOGT, and QUI1 (Figure 1).

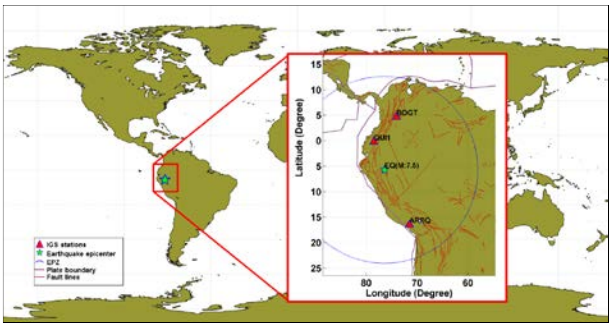

Figure 1. 2005 Northern Peru earthquake preparation zone and IGS stations

The IGS RINEX files, SP3 (precise satellite orbits) files, and IGS IONEX (Ionospheric TEC maps and Satellite DCBs) files were obtained from the GNSS data and products archive of Crustal Dynamics Data and Information System to investigate the anomalous variations on ionospheric TEC during the earthquake. These data are available from the website ftp://cddis.gsfc.nasa.gov. In the current study, we estimated GPS-TEC data, which were obtained from the GNSS stations near the epicentre of the earthquake, by using surface polynomial fitting. Anomalous variation in TEC was determined by using the quartile-based statistical analysis method [23]. [23] used GIM-TEC (2-hour resolution) data for the earthquake epicentre. In the current study, we estimated GPS-TEC data (1-hour resolution).

Hourly GPS-TEC data for the days between August 27 and October 24, 2005, were processed by following the methodology explained in Section 2. TEC data were analyzed using the 15–day MM method analyzed using the methodology explained in Section 3. The reliability of the estimated GPS-TEC values was checked by comparing their values with GIM-TEC values obtained from IGS IONEX files. The daily mean values and RMS of differences between the GPS-TEC and IGS IONEX file values for IGS stations were then calculated (Figure 2).

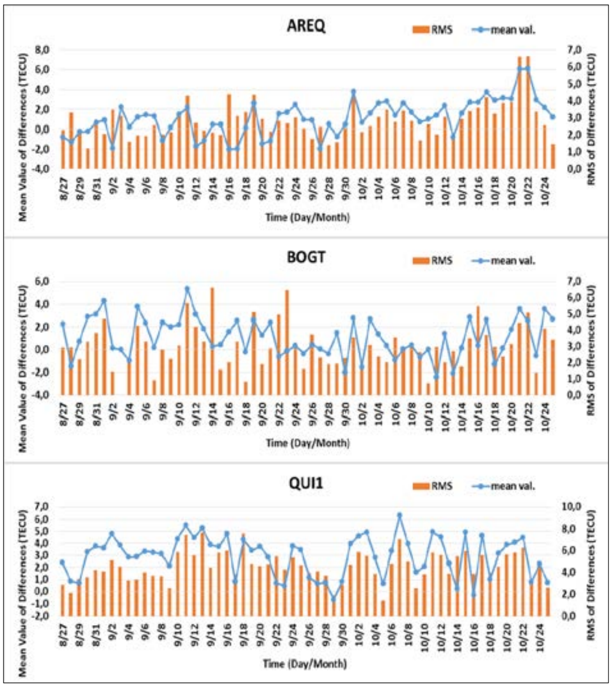

Figure 2. Daily mean values and RMS of differences between the GPS-TEC and VTEC from IGS IONEX files

The accuracy of IGS IONEX TEC values were defined in the range of 2-8 TECU (https://igscb.jpl.nasa.gov/components/prods.html). The results in Figure 2 shows that the calculated mean and RMS of GPS-TEC values are within the acceptable range and hence can be considered reliable.

The ionospheric parameters are affected by solar-geophysical conditions and geomagnetic storms, especially in the Equatorial and Polar Regions. When discussing the relationship between ionospheric anomaly and earthquake, the solar-terrestrial environment must be considered to exclude anomalies that may have been caused by solar or geomagnetic activities [29, 31]. Geomagnetic and solar indices (i.e., Dst, Kp, and F10.7) are obtained for space weather conditions (SWC). We accessed the geomagnetic storm indices (Dst) from the archive of the Data Analysis Center for Geomagnetism and Space Magnetism Graduate School of Science of Kyoto University via the link http://wdc.kugi.kyoto-u.ac.jp/dstae/index.html. The Kp indices data from the National Oceanic and Atmospheric Administration are archived in ftp://ftp.ngdc.noaa.gov/STP/GEOMAGNETIC_DATA/INDICES/KP_AP/. The solar radio flux (F10.7cm) data from the Canadian Space Weather Forecast Center in Ottawa were obtained from http://www.spaceweather.gc.ca/solarflux/sx-en.php. In this study, we investigated the geomagnetic and solar indices (Dst, F10.7, and Kp) to distinguish seismic anomalies from other anomalies related to space weather conditions from the period from September 11 to October 10, 2010 (Figure 3).

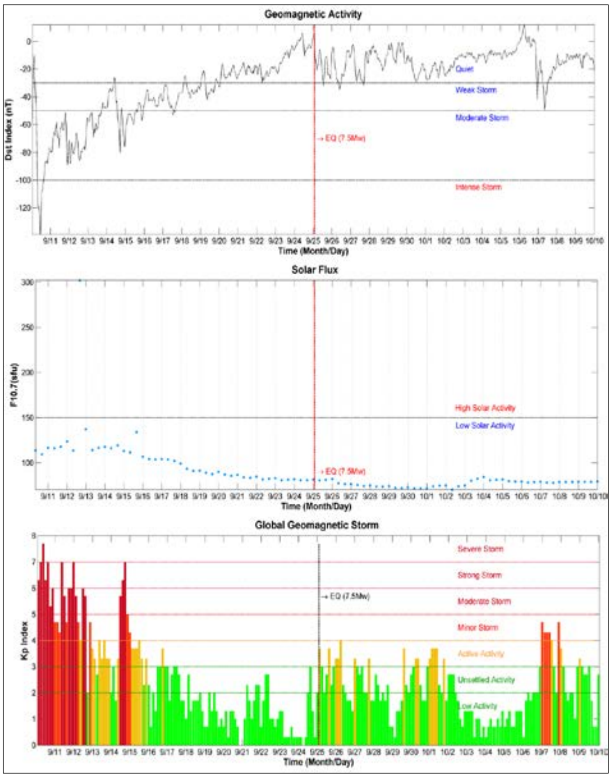

Figure 3. Variations in the solar radio flux and the geomagnetic activity index between September 11 and October 10, 2005

[2] and [5] indicated the possibility of classifying solar activity in terms of the F10.7 Index. Solar fluxes less and more than 150 sfu indicate low and high solar activities, respectively. In Fig. 3, solar activity values were lower than 150 sfu between September 11 and October 10, 2005. [6] and [33] established three classes of geomagnetic storms according to the magnitude of the storms, namely, weak ($Dst_{min} > -50$ nT), moderate ($-50 \text{ nT} > Dst_{min} > -100$ nT) and intense ($Dst_{min} < -100$ nT). In Figure 3, negatively peaked Dst index values is -139 nT on September 11, 2005. Moderate storm occurred between the dates September 12 and 16, 2005. Quiet geomagnetic activity occurred from September 17 to September 26, 2005. The Kp indices range from “0” (very quiet) to “9” (extremely disturbed). Kp indices between “0” and “3” values are classified as very low and unsettled storm, respectively. Kp indices between “4” and “5” are classified as an active and minor storm, and Kp indices between “5” and “9” are

classified as minor storm and extreme storm, respectively [41]. In Fig. 3, Kp index values are very high and reaches 7.7 (severe storm), 7 (strong storm) and 7 (strong storm) on September 11, 12, and 15, 2005, respectively. According to Fig. 3, space-weather conditions were very low between September 17 and 25, 2005 and the earthquake occurred at quiet conditions.

The LBs, UBs, and MM values were calculated as occurring in the same period as the space -weather conditions data by using daily variations in the one-hour resolution of GPS-TEC data calculated from selected IGS sites close to the earthquake epicenter. The number of VTEC anomalies was determined from the percentage of daily VTEC anomalies. The percentage limit of anomalous VTEC was determined as ~33% (eight hours are anomalous in a day). GPS-TEC variations over each stations and ratio of the upper and lower anomalous days between the dates September 11 - October 10, 2005, is shown in Fig. 4.

The GPS-TEC time series data shown in Fig. 4 clearly indicate that the obvious positive anomalies started to occur four-nine days before the 2005 Northern Peru earthquake. However, Figure 3 clearly shows that space-weather conditions were very low between September 17 and 25, 2005 and the earthquake occurred at quiet conditions. These days had suitable space weather conditions for investigation of seismo-ionospheric effects of the earthquake. Figure 4 clearly shows that, for all sites, VTEC values were 5-22 TECU higher than the UB (positive anomaly: black colored areas) on the days (September 17 and 18, 2005) before the earthquake. All calculated ratio of anomalous VTEC variations of all stations until the earthquake are given in Table 1.

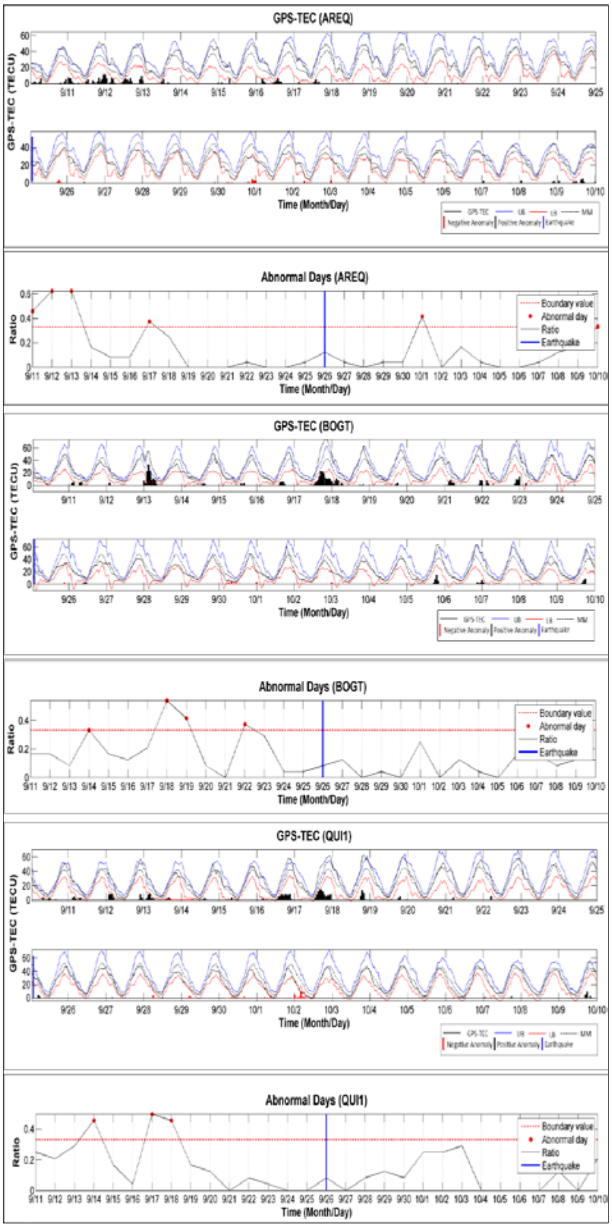

Figure 4. GPS-TEC variations over each stations and ratio of the upper and lower anomalous days between the dates September 11- October 10, 2005

Table 1. Ratio of anomalous VTEC variations in quiet space-weather conditions

Site	09.11	09.12	09.13	09.14	09.15	09.16	09.17	09.18	09.19	09.20	09.21	09.22	09.23	09.24	09.25	09.26
AREQ	0.49	0.63	0.63	-	-	-	0.38	-	-	-	-	-	-	-	-	**EARTHQUAKE**
BOGT	-	-	-	0.33	-	-	-	0.54	0.42	-	-	0.38	-	-	-	
QUI1	-	-	-	0.46	-	-	0.50	0.46	-	-	-	-	-	-	-	
SWC	A	A	A	A	A	Q	Q	A	Q	Q	Q	Q	Q	Q	Q	

As shown in Table 1, the ratio calculated after September 11, 2005, could be related to the geomagnetic storm and geomagnetic activity, which ended on September 16, 2005. The first anomalous variation in the quiet space-weather conditions (September 17 and 25, 2005) are occurred on September 17, 2005 (nine days before the earthquake) on AREQ and QUI1 IGS stations and on September 18, 2005 (eight days before the earthquake) on BOGT IGS station.

5. Conclusions

We investigated the ionospheric VTEC anomalies for the 2005 Northern Peru earthquake by analysing the possible causes of these anomalies based on space weather conditions. Geomagnetic activity (Dst), solar activity (F10.7), and geomagnetic storm (Kp) indices were examined. The indices showed that the status of the space environment and magnetic field was quiet between September 17 and September 26, 2005. Hence, we conclude that the 2005 Northern Peru earthquake occurred under quiet space-weather conditions. Ionospheric GPS-TEC values were determined by using GNSS data. The VTEC values on September 17, 18, 13, and 22, 2005 were approximately 5-22 TECU higher than the UB values. In this regard, the abnormal change in GPS-TEC variations four to nine days before the earthquake may be considered as the ionospheric precursor of the 2005 Northern Peru earthquake.

This paper focuses only on demonstrating the ionospheric variability prior to the 2005 Northern Peru earthquake. The detailed aspects of physical mechanism of the seismo ionospheric activity were already examined in many researches [24, 25, 32, 39]. The previous studies related to this earthquake [22, 38], were confirmed the ionospheric anomalies occurring a few days prior to the earthquake.

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