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GPS–TEC НАБЛЮДЕНИЯ ПЕРЕД ХУБСУГУЛЬСКИМ ЗЕМЛЕТРЯСЕНИЕМ Mw6.7 11 ЯНВАРЯ 2021 Г. В МОНГОЛИИ

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THE OBSERVATION OF GPS-TEC BEFORE Mw6.7 KHUVSGUL EARTHQUAKE ON JANUARY 11, 2021 IN MONGOLIA

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Аннотация. Исследовалось полное электронное содержание (TEC) в ионосфере по измерениям GPS непрерывно действующих опорных станций перед Хубсугульским землетрясением Mw6.7 11 января 2021 г. Мы использовали 16 опорных станций включая 8 станций в зоне подготовки землетрясения и другие 8 станций вне зоны для сравнения в течение 30 дней до землетрясения. Аномалия в вариациях TEC определялась по отклонению от границ, рассчитанных с помощью метода главных компонент. Кроме того, чтобы исследовать факторы, вызывающие вариации TEC, отдельно от сейсмического процесса, анализировались индексы геомагнитной (Dst, K_p) и солнечной (вспышки, F10.7) активности. Результаты показали, что отчетливо выраженное нарастание TEC наблюдалось по всем станциям на 19–20 день до землетрясения, что, возможно, было связано с геомагнитной активностью. Однако в основном положительные отклонения в вертикальном TEC были обнаружены на 12–13 и 2–3 дни до землетрясения по большинству станций во время периода спокойной космической погоды. Поскольку эти аномалии наблюдались и внутри и вне зоны подготовки землетрясения в обширной области континента, требуется дальнейшее исследование для отождествления этого эффекта.

Ключевые слова: GPS-TEC, аномалия TEC, предвестник землетрясения, Хубсугульское землетрясение Mw6.7.

Abstract. In this paper, we examined the total electron content (TEC) in the ionosphere measured by GPS based continuously operating reference stations (CORS) before Mw6.7 earthquake occurred on January 11, 2021. We used 16 CORS stations including eight stations in an earthquake preparation zone and other eight stations outside the zone for the comparison throughout 30 days prior to the earthquake. The anomaly in TEC variations was identified by deviation from limits calculated by principal statistical method. Moreover, to analyze the inducing factors for TEC variation aside from seismic process, the results were analyzed with geomagnetic activity (Dst, K_p) and solar activity (flares, F10.7). The results show that distinct increment in the TEC observed on 19–20th day over all stations prior to the earthquake which is possibly associated to the geomagnetic activity. However, mostly positive deviations in vertical TEC is detected on 12–13th day and 2–3rd day prior to the earthquake over most of stations during a quiet space weather period. Since these abnormalities are observed on both in and outside the earthquake preparation zone within the vast region of continent, further investigation is required to distinguish the effect.

Keywords: GPS-TEC, TEC anomaly, Earthquake precursor, Mw6.7 Khuvsgul earthquake.

INTRODUCTION

Earthquake prediction has been always one of the most concerning studies for not only seismologist but also researchers from broad backgrounds as it possesses risk to human life and property. Before LAIC model, which interprets physical processes rising before earthquake as a complex system [Pulinets, Ouzounov, 2011], earthquake prediction was limited only to elusive seismic data analysis [e.g., Matsumura, 2009; Geller, 1997] and geological approach. However, as postulated in LAIC model, short term earthquake precursors would be observed in the atmosphere and ionosphere associated with the earthquake preparation process such as emanation of various gaseous [Pulinets, 2004] and formation of positive holes [Freund, 2009; Grant et al., 2015]. Following the discovery of ionospheric disturbance before Alaska 1964 earthquake [Leonard et al., 1965], ionospheric precursors has emerged as a promising parameter in pre-earthquake phenomenal study [Parrot, 1995; Freund, 2009; Pulinets, Ouzounov, 2011; Le et al., 2011; Piscini et al., 2017; Liu, 2018; Ouzounov et al., 2021]. For instance, Pulinets [2007] and Liu et al. [2000] observed noticeable decrease in f_oF_2 layer of ionosphere before certain strong earthquakes. Also, Liperovsky et al. [2005] discovered increase in ionospheric E layer disturbance before great earthquakes.

In addition, total electron content (TEC), the descriptive parameter in the ionosphere, has been analyzed in numerous studies using measurements derived from ground-based instrumentations, such as GPS receivers and Ionosonde [e.g. Zaslavski et al., 1998; Liu et al., 2000, 2004; Guo et al., 2015; Sharma et al, 2020]. According to the results, TEC anomalies, depletion or enhancements, were detected before strong earthquakes occurred around the world. Specifically, GPS derived TEC variations demonstrated a possible pre-earthquake TEC anomaly between 0 and 20 day before earthquakes by [Pulinets, 2009, Liu et al., 2011, etc].

Mongolia is seismic prone country, recently Mw6.7 earthquake where occurred on Jan 11, 2021 in Khuvsgul province. The epicenter was located at 51.3285° N and 100.3744° E. As it is recent moderate seismic event, we examined its possible pre-earthquake ionospheric precursor.

DATA AND METHOD

In this study, we used data from 16 CORS stations including eight in earthquake preparation zone (EPZ) and eight outside the zone for 30 days prior to the earthquake. The EPZ radius is determined by the equation dependent of moment magnitude of the earthquake [Dob-

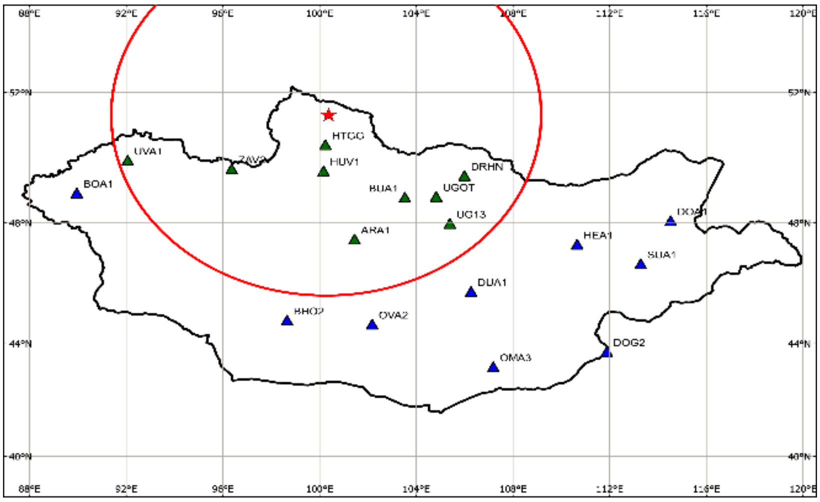

Figure 1. GPS stations used in the study

rovolsky et al., 1979] $R=10^{0.43M}$, where R is the EPZ radius from earthquake epicenter [km] and M is moment magnitude of selected earthquake. The EPZ radius is estimated to be 624 km for the Mw6.7 earthquake. The zone is shown in Figure 1 by red circle. Also, red star represents the earthquake epicenter, green and blue triangles represent CORS stations in EPZ and outside EPZ respectively.

GPS receiver data were processed by open source software called GPS-TEC developed by Gopi Seemala. TEC along the slant ray paths between a satellite and a ground station (sTEC) is calculated by difference between pseudo-ranges P1 and P2 as the following equation [Blewitt, 1990]:

$$sTEC = \frac{2\left(f_1 f_2\right)^2}{K\left(f_1^2 - f_2^2\right)}\left(P_2 - P_1\right),$$

where f_1 and f_2 are GPS signal frequencies (f_1=1575.42 MHz and f_2=1227.60 MHz) and K=80.62 (m^3/s^2) is a constant that relates the plasma frequency to the electron density. TEC is reported in TEC unit, where 1 TECU=10^{16} el/m^2. Also, vertical TEC which considers zenith angle and biases of satellite and receiver can be obtained as,

$$vTEC = \left(sTEC - b_s - b_r\right)\arcsin\sin\left(\frac{R_E \cos\cos\alpha}{R_E + h}\right),$$

where b_s and b_r are the estimated satellite and receiver biases [Ma, Maruyama, 2003; Sharma et al., 2020]. The satellite and receiver biases files (p1p2 and p1c1) were obtained from CODE analysis data center, university of Bern (AIUB), and orbit files (Sp3) were obtained from IGS.

Furthermore, for the identification of seismo-ionospheric anomaly, the running median of 15 days $(\overline{TEC})$, considering diurnal and seasonal variations, and standard deviation σ were computed to construct the upper and lower bounds.

$$\text{Upper Boundary}\left(UB\right) = \overline{TEC} + 1.5\sigma,$$

$$\text{Lower Boundary}\left(LB\right) = \overline{TEC} - 1.5\sigma,$$

vTEC values above the upper bound or below the lower bound are considered as anomaly. In this paper, TEC anomaly is expressed as $dTECU$.

$$dTECU \begin{cases} TEC - UB, \; while \; TEC > UB, \\ 0, \; while \; TEC < UB, TEC > LB, \\ LB - TEC, \; while \; TEC < LB. \end{cases}$$

GEOMAGNETIC AND SOLAR ACTIVITY DURING THE OBSERVATION

Aside from earthquake, there are various inducing factors for TEC disturbance. Hence, we considered solar and geomagnetic activity factors to discriminate the detected anomaly due to the earthquake. Disturbance storm time index Dst and geomagnetic index K_p are presented to measure geomagnetic activity. Dst and geomagnetic three-hour K_p data is obtained from World Data Center for Geomagnetism, Kyoto University and GFZ German Research Centre for Geosciences, respectively. As for the solar activity magnitude, since there were no significant solar flares to affect the ionospheric disturbance, solar radio flux at 10.7 cm index $F10.7$ is presented [retrieved from NOAA]. These indices during the observation period are illustrated in Figure 2.

For solar-geomagnetic active period, where those indices exceed the following limits, $Dst \ll -30$ nT, $K_p>4$ and $F10.7>150$ sfu [Zhu et al., 2010; Fuying et al., 2011], it is hard to distinguish the seismo-ionospheric anomaly from the space weather's. Figure 2 shows that solar and geomagnetic activities for 30 days prior to earthquake was relatively quiet, because Dst was not lower than –30 nT and $F10.7$ was lower than 150 sfu. However, K_p on 21st day and 19th day pre-earthquake was peaked at 4.3, which indicates that minor geomagnetic storms on those days.

OBSERVATION RESULTS

The earthquake was occurred at 21:32 LT on Jan 11, 2021 in Khuvsgul province of Mongolia. In the study, we analyzed 30 days TEC derived from GPS observation prior to the earthquake. Firstly, TEC data derived from

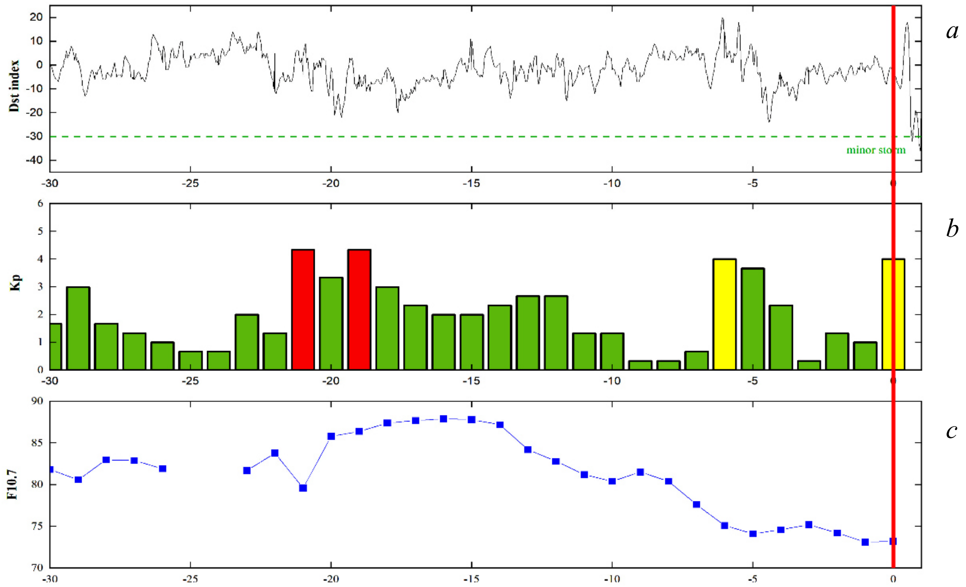

Figure. 2. Disturbance of solar activity and geomagnetic activity from Dec 12 to Jan 11 (UTC): time series of *Dst* (*a*), K_p, (*b*), *F*10.7 (*c*)

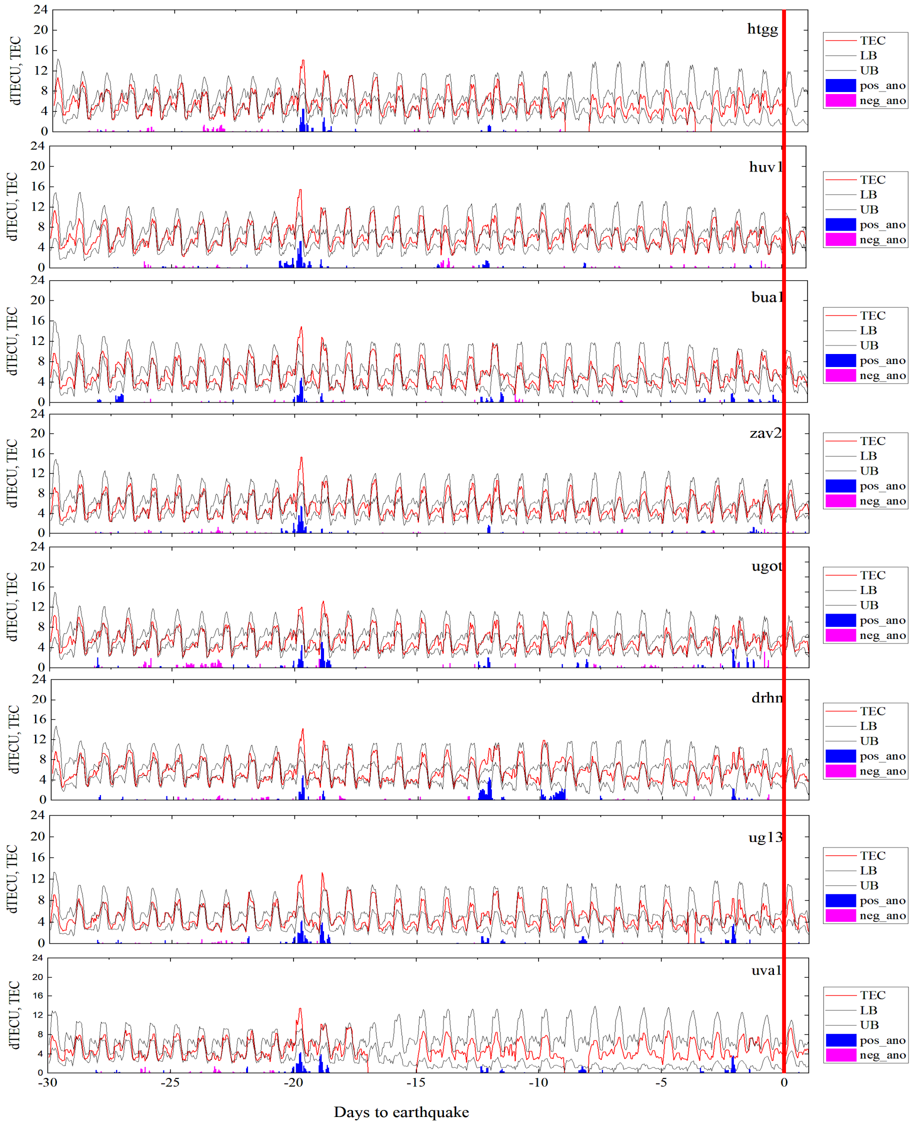

Figure 3. TEC values observed for 30 days derived from eight stations in the earthquake preparation zone in which vertical red line indicates earthquake time. Also, blue and pink columns show positive and negative anomaly respectively if the TEC value crosses boundaries

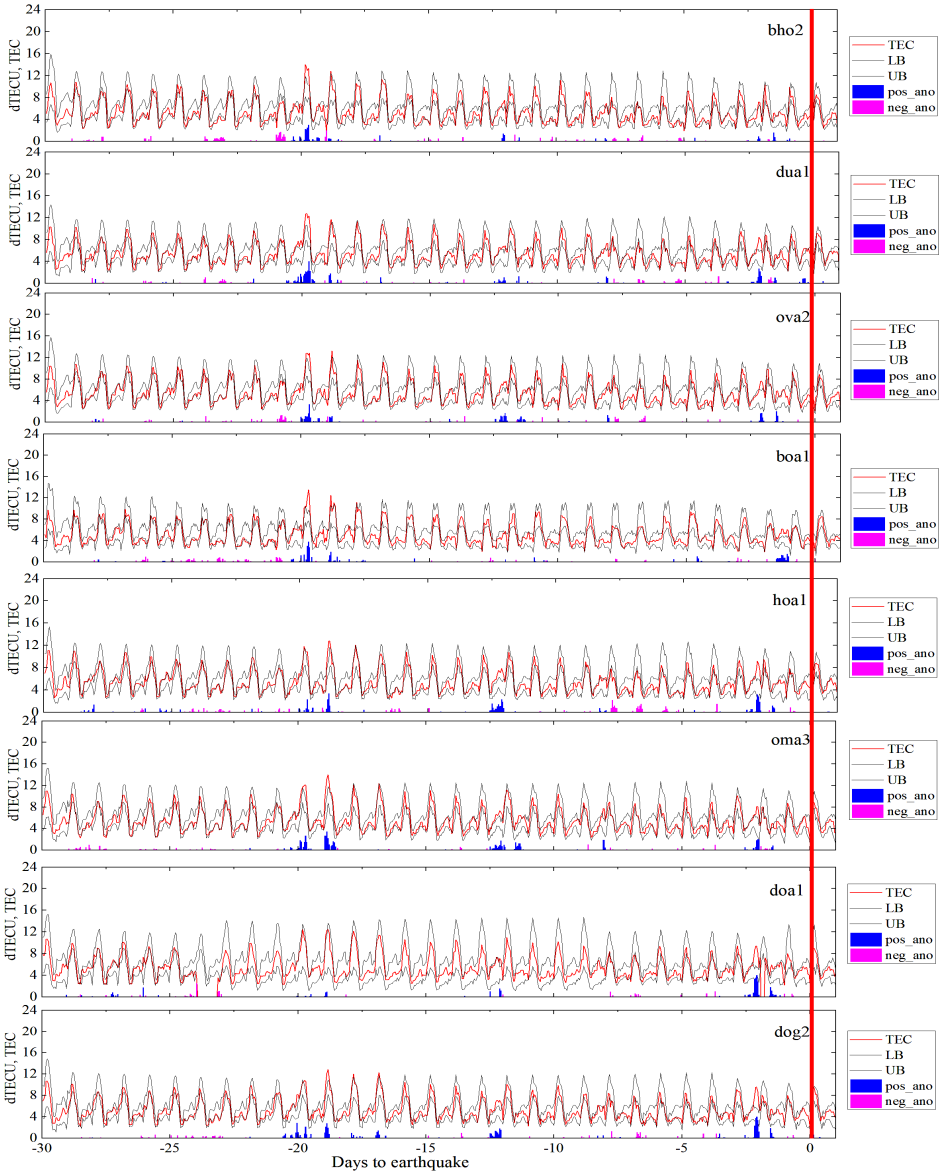

Figure 4. The same as in Figure 3 outside the earthquake preparation zone

eight GPS receivers located in the EPZ with distance of 110–610 km from epicenter were investigated. TEC time series over stations lying in EPZ, and their upper and lower boundaries are illustrated in Figure 3, in increasing order of distance from epicenter. The anomalies determined using statistical technique as moving median and standard deviation is also included in the graph. Positive and negative anomaly in TECU is embodied by blue and pink color columns respectively. The result shows multiple solid positive anomalies over almost all stations, including 19–20th, 12–13th and 2–3rd days prior to the earthquake. The most noticeable anomaly observed throughout 19–20th day. TEC increased in average of 4–6 TECU for all stations. Specially, for the nearest stations from epicenter (htgg and huv1), it went up by 4.6 TECU and 5.33 TECU. An increment of 1.4 TECU lasting more than three hours is observed on 12–13th day for all stations except “drhn”, where the value is measured as 3.5 TECU. Even though variation is not detected in all stations, approximately 4 TECU deviation is detected in most stations around 2–3 days before earthquake.

Moreover, the same observation is done for eight stations located outside of the EPZ in order to compare results and distinguish the source of ambiguity (Figure 4). The stations are located at the distance of 750–1200 km from earthquake epicenter. As shown in Figure 4, positive anomaly of 3–4 TECU is detected on 19–20th day as same as stations in EPZ, whereas the value was 1–2 TECU unit lower. The result could be explained in regards to distance from station to earthquake epicenter. Because higher *dTECU* is observed in stations inside EPZ than outside. The anomalous pattern of 12–13th day is also detected on four stations outside the EPZ. The detected *dTECU* was lower than the previous results. Thus, same explanation could be given. Inversely, for stations outside the EPZ, TEC variation on 2–3rd day is observed greater than the stations inside EPZ.

Furthermore, to explain the anomalies, we compared the result of analysis on geomagnetic and solar activity during the observation period. The geomagnetic K_p index shows anomalous result on 19th and 21st day prior the earthquake, which coincidence with the TEC disturbances. So, the overall TEC variation on 19–20th day is most likely to be forged due to the geomagnetic disturbances. However, solar-geomagnetic activity was quiet during the 2–3rd day and 12–13th day events, unlike the 19–20th event.

CONCLUSIONS

The main objective of this study was to document our observations and to acquire a better understanding of the TEC disturbances in the ionosphere before earthquake. The observation results detected multiple solid positive anomaly 30 days before the earthquake.

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