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Anamolous Ionospheric TEC Variations Prior to the Indonesian Earthquake (M 7.1) of November 15, 2014[1]

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Abstract—This paper investigates preearthquake ionospheric variations with the use of TEC of Global Ionospheric Maps (GIMs) and regional maps based on Precise Point Positioning (PPP) during the 7.1-M Indonesian earthquake that occurred on November 15, 2014. TEC maps corresponding to 10 days before to 4 days after the event were examined. In addition, a time series of TEC values according to the PPP maps were also evaluated. In addition to GIMs, it was possible to detect TEC variations with PPP maps. The results showed that ionospheric TEC decreased strikingly 4 days prior to the earthquake. This TEC variation was highly likely related to seismic activity.

Keywords: Earthquake, GIMs, Ionosphere, PPP, TEC

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1. INTRODUCTION

Earthquakes, particularly large earthquakes, cause massive destruction and much loss of human life. In order to measure the size of earthquakes in terms of released energy, the Moment Magnitude Scale (MMS), denoted as *Mw* or *M*, is used. Thus, earthquake prediction is of great importance. In research on earthquake prediction, ionospheric effects produced by seismic activity has become an important topic for seismologists (Zhu et al., 2014). The main difficulty in identifying earthquake effects is ionospheric variation, which is caused by many factors, e.g., geomagnetic field changes, solar flares, etc. Preearthquake ionospheric anomalies were first discussed by Leonard and Barnes (1965) for the Alaskan earthquake that occurred in 1964. Many studies have been undertaken to identify earthquake precursors and have verified the ionospheric variations associated with seismic activity appearing prior to the event (Zhu et al., 2014; Zakharenkova et al., 2006, 2008; Zhou et al., 2009; Dogan et al., 2011, Krankowski et al., 2006; Liu et al., 2009, 2011). GNSS (Global Navigation Satellite System) and ionosonde data have mainly been used in recent years to analyze preearthquake ionospheric anomalies. However, since less than 300 ionosondes are available and only a fraction of them are continuously operational, it is mostly GNSS data that are used (Zhou et al., 2009).

Using TEC data from the Global Ionosphere Map (GIM), Liu et al. (2011) investigated seismoionospheric anomalies associated with the M7 Haitian earthquake. The results indicated that the anomalous behavior of the TEC one day before the earthquake is highly related to the earthquake. Using GPS data, Dogan et al. (2011) studied the ionospheric response to the large earthquake. According to the observational results, a negative anomaly was detected three days before the event, reaching a 10-TECu level relative to the nondisturbed state. Perevalova et al. (2014) examined the ionospheric wave disturbances induced by earthquakes of different magnitudes. The results revealed that wave disturbances in TEC variations of 4.1–6.3 magnitude earthquakes are undetectable. The response to earthquakes with 6.5–6.7 is hard to distinguish at the level of background oscillations. In addition, TEC disturbances triggered by strong earthquakes with $7.2 < Mw < 8.8$ are registered with confidence. However, not all strong earthquakes revealed anomalous ionospheric disturbances during their preparation process due to the geomagnetic activity. Afraimovich et al. (2004) investigated the TEC variations during the 7.1-*Mw* Hector Mine earthquake of October 16, 1999 in California. Analysis demonstrated that the TEC variations seem to have been controlled by the local time and fairly moderate geomagnetic activity rather than by any expected process that usually accompanies the process of earthquake preparation. Le et al. (2011) and Zhu et al. (2014) conducted statistical studies on the temporal distribution of ionospheric anomalies with a magnitude of $M \geq 6.0$ and $M \geq 7.0$ respectively. The results illustrated that the anomalous behavior of the TEC just a few days prior to

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the earthquakes is related to the subsequent earthquakes with a high probability.

The goal of this study is to examine the ionospheric variations before the strong (M7.1) earthquake that occurred 155 km northwest of the Kota Ternate, Indonesia, at 0231 UT on November 15, 2014. The epicenter of the event was 1.900° N 126.523° E. In addition to global ionospheric maps, regional maps associated with Precise Point Positioning (PPP) were used in the present study to examine ionospheric TEC anomalies before the Indonesian earthquake.

2. GEOMAGNETIC AND SOLAR CONDITIONS

Geomagnetic disturbances that cause large ionospheric perturbations can complicate the detection of seismo-ionospheric variations (Krankowski et al., 2006). Figure 1 represents the geomagnetic (*Dst*, *Kp*, *ap*) and solar activity index (*F*10.7) values from 10 days before to 4 days after the earthquake (November 5–19, 2014). Geomagnetic indices were derived from the International Service of Geomagnetic Indices (ISGI) website (http://isgi.latmos.ipsl.fr), while the solar activity index values were obtained from the website of the Space Environment Prediction Center (SEPC) (http://engsepc.ac.cn/F107Index.php).

As seen in Fig. 1, the geomagnetic and solar conditions are suitable for the detection of seismo-ionospheric anomalies. The *Kp* index values are less than 5, and the *Dst* values are larger than –30 nT except for those of November 10, 2014. In addition the solar activity index (*F*10.7) values are stationary, and there is no sudden increase that could negatively influence the detection of the preseismic anomalies.

3. DATA SOURCES

In order to analyze the preseismic modification of the ionosphere, the global Vertical Total Electron Content (VTEC) maps in the IONsphere map Exchange (IONEX) format and PPP-based regional VTEC maps, hereinafter referred to as TEC maps, were employed. The IONEX data are accessible at the site ftp://ftp.unibe.ch/aiub/CODE. The global TEC maps were generated routinely with a spatial resolution of 5° longitude and 2.5° latitude and a time interval of 2 h until October 2014. Since then, TEC maps have been generated at a temporal interval of 1 h. Thus, TEC maps corresponding to a 1-h interval were used in this study.

In addition to TEC maps, PPP-based regional maps were generated withe Bernese 5.0 GNSS software (Dach and Hugentobler, 2007). The PPP method is a special case of zero difference processing that requires only one station for the processing. With a single station, it is possible to observe a given part of the ionosphere. The dimension of this area can be defined by the "coverage circle" concept with the following equations (Hugentobler et al., 2001).

$$\sin z' = \frac{R}{R+H}\sin z, \tag{1}$$

$$\tan(z - z') = \frac{r}{R+H}. \tag{2}$$

Where R is the radius of the earth, H is the height of the single layer above the earth surface. While r is the radius of the coverage circle, z and z' denote zenith distances at the height of the station and single layer respectively. When a single-layer height of 450 km and 15° cut of angle are used, the ionosphere can be observed with a radius of ~1270 km at each station. Similar to the GIMs, a 1-h time interval was chosen; however, regional TEC maps were generated with a resolution of 1°.

4. DATA ANALYSIS AND INTERPRETATION

In data analysis, statistical analysis is generally used. It has been previously applied in the description of the TEC variations associated with earthquakes (Zhou et al., 2009; Zhu et al., 2013). Thus, an effort has been made to carry out statistical analysis by investigating the ionospheric TEC variations before the Indonesian earthquake. In order to construct the upper ($\bar{x} + 2\sigma$) and lower bound ($\bar{x} - 2\sigma$), the mean $\bar{x}$ of the previous 10-day TECs for the same time intervals and the associated standard deviations σ were computed. The range from ($\bar{x} + 2\sigma$) to ($\bar{x} - 2\sigma$) forms the normal reference. If the TEC value falls out of either the associated upper or lower bound, then it is defined as a positive or negative anomaly with a confidence level of about 95% (Zhou et al., 2009; Zhu et al., 2013). In other words, if the difference between the observed TEC and mean value (ΔTEC) was less than twice the standard deviation set to ΔTEC = 0, ΔTEC < 0 indicates a negative anomaly and ΔTEC > 0 represents a positive anomaly.

In this study global ΔTEC maps were examined to detect whether they represent any preseismic anomaly. A negative anomaly was detected 4 days prior to the earthquake November 11, 2014). Figures 2–4 demonstrate the global ΔTEC maps corresponding to 4 days before the event from 0000 UT to 1300 UT with a time interval of 1 h.

As Figures 2–4 show, the ionospheric anomaly began at 0200 UT, close to the epicenter; it is depicted as a dot in all of the maps. The most affected area was located roughly 7° W, 100° E, reaching a maximum ΔTEC of 27 TECu at 0800 UT. This anomaly disappeared gradually after 1300 UT. As was previously shown by the index values, geomagnetic and solar conditions could make it possible to detect preseismic anomaly. There was no significant ionospheric anomaly in the rest of the world at this time. The iono-

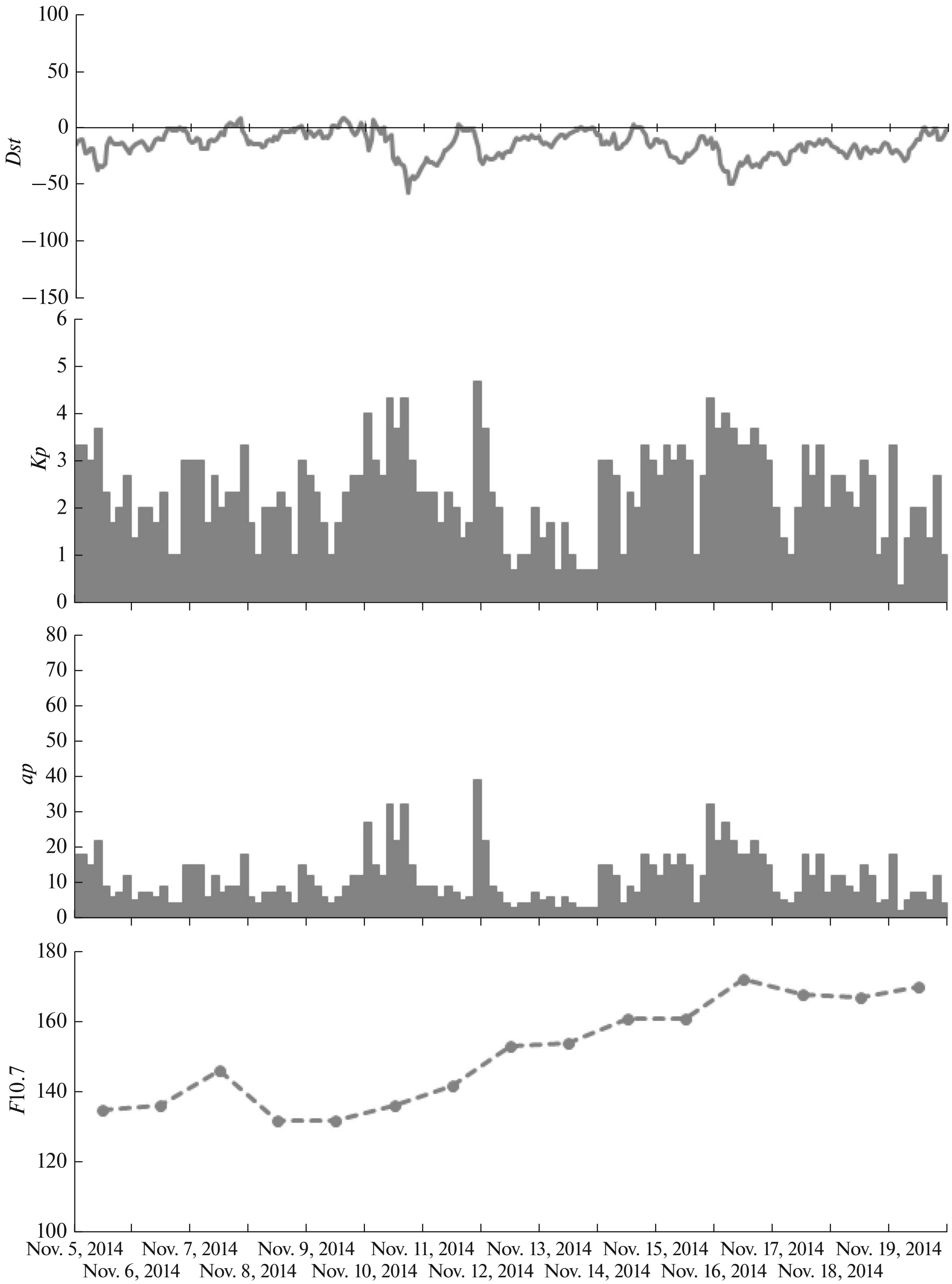

Fig. 1. *Kp*, *ap*, *Dst*, and *F*10.7 index values for November 5–19, 2014.

spheric anomalies caused by solar and geomagnetic field activities generally manifest over a wider geographic range (Yao et al., 2012). An example of this condition is given by Alcay (2016). Thus, the ionospheric anomaly observed on November 11 appeared only near the epicenter, and its duration was comper-

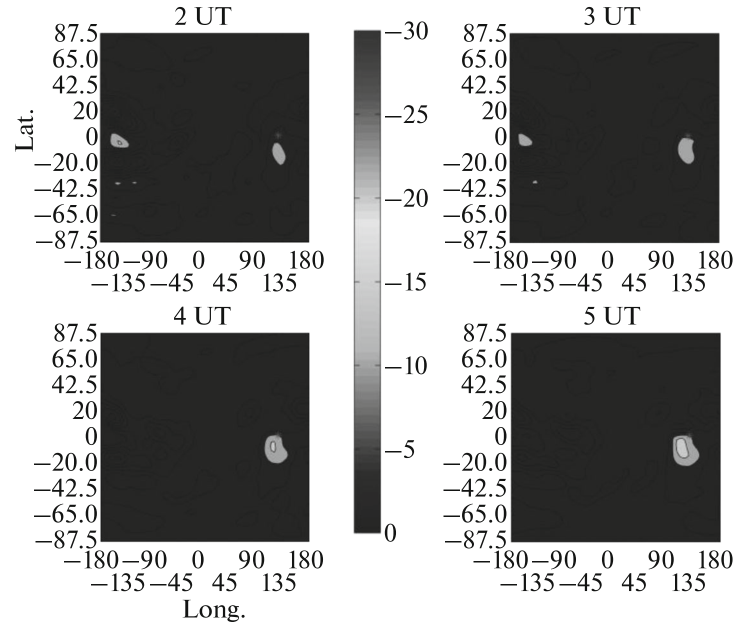

Fig. 2. Global ΔTEC maps of November 11 from 0200 –0500 UT.

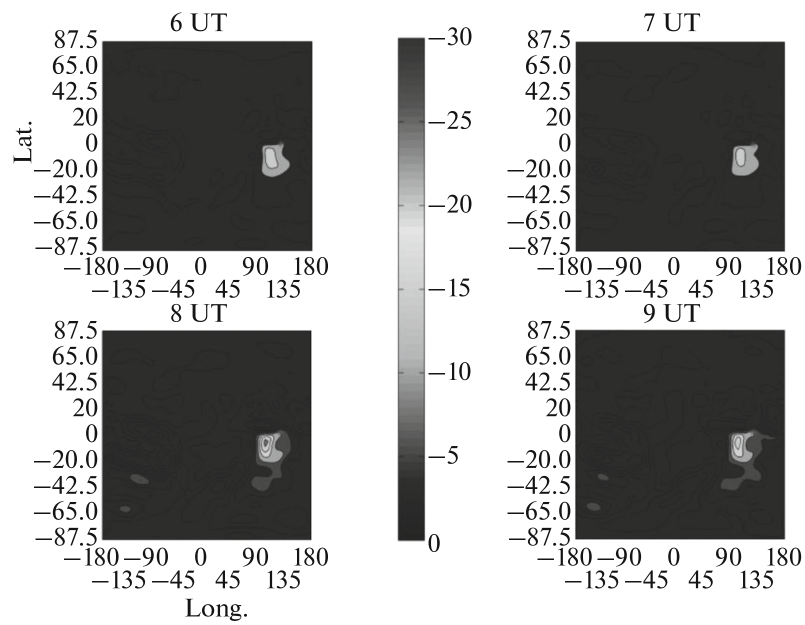

Fig. 3. Global ΔTEC maps of November 11 from 0600–0900 UT.

atively long, providing evidence that it was associated with the proceeding earthquake.

Along with global TEC maps, PPP-based regional TEC maps were generated with data from XMIS IGS station, which is nearer to the anomalous region. According to the coverage circle concept given in the previous subsection, PPP TEC maps were estimated for 2°–18° S and 97°–113° E. In order to view the influence of the anomaly clearly, a time series of PPP TEC values corresponding to the epicenter of the anomaly (7° S, 100° E) were excluded from PPP maps. Figures 5 and 6 show the TEC time series, the mean, and the upper and lower bounds.

As is shown in Fig. 5, similar to the global ΔTEC maps, a negative anomaly was observed on November 11; it is denoted as a blue circle. The TEC decrease began at 0600–0800 UT and reached 30–33 TECu relative to the lower bound. The TEC values of the remaining

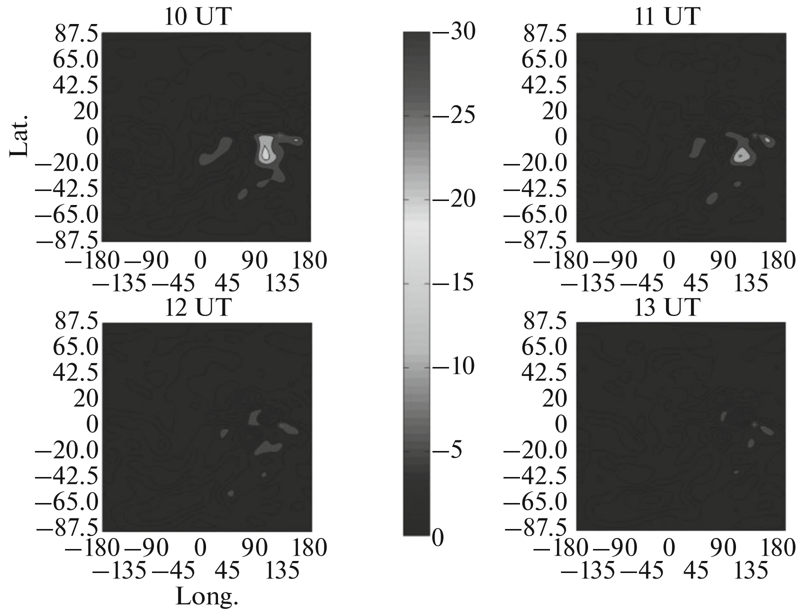

Fig. 4. Global ΔTEC maps of November 11 from 1000–1300 UT.

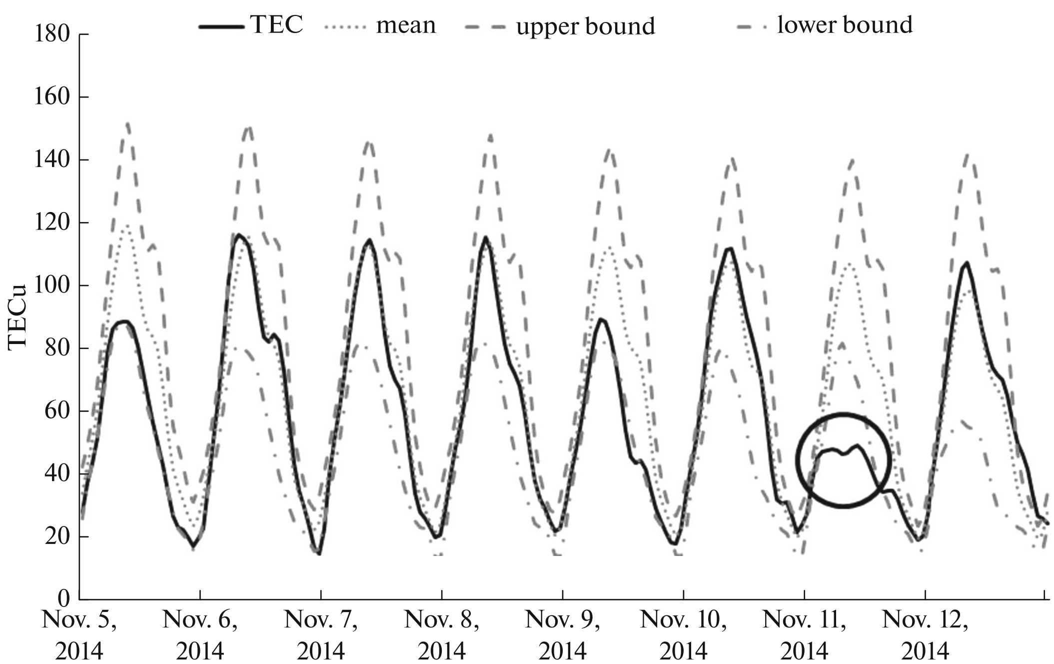

Fig. 5. Time series of PPP maps corresponding to −7° lat./100° long. for November 5–12.

days were generally close to the mean values. Hence, the occurrence of a seismo-ionospheric anomaly a few days before the eathquake is quite well explained, as is seen in Fig. 5.

5. CONCLUSION

This paper characterizes the ionospheric variability prior to the Indonesian earthquake of November 15, 2014, with the use of GIMs and PPP-based regional ionospheric maps. Similar results were observed in both global and regional maps. A negative anomaly was detected 4 days prior to the earthquake. However, the highest level of the anomaly was 4–5 TECu higher in the PPP results. This is most probably related to the global nature of GIMs. Consideration of the geomagnetic and solar conditions, as well as the region of the anomaly and its duration, made it possible to associate

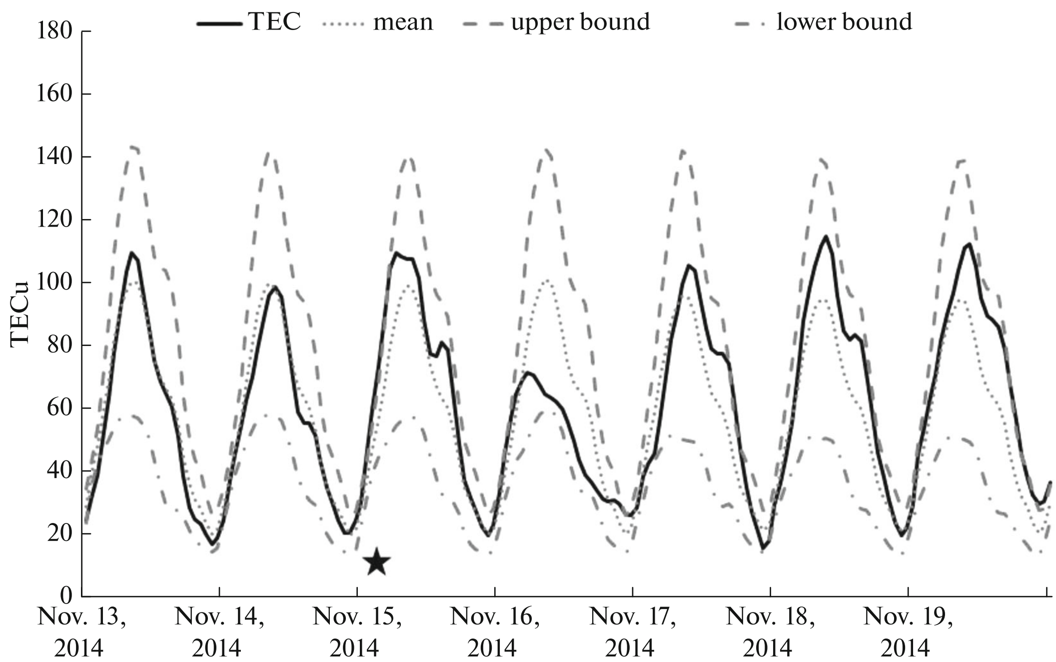

Fig. 6. Time series of PPP maps corresponding to –7° lat./100° long. for November 13–19 (red star denotes the time of the earthquake).

the anomaly with the earthquake with a high probability. As noted in the previous studies (Zakharenkova et al., 2006; Liu et al., 2011; Yao et al., 2012; Zhu et al., 2013; etc.), this study confirmed that ionospheric perturbations do exist a few days prior to the earthquake. In addition this paper also showed that PPP-based regional ionospheric maps are useful in research on the ionospheric variations associated with earthquakes.

The present study focused only on the ionospheric TEC variations prior to the earthquake. It was not intended to discuss the physical mechanism of seismo-ionospheric effects, which have already been examined in many studies (Varotsos et al., 2001; Sorokin et al., 2001; Shinagawa et al., 2007; Liu et al., 2011; Zolotov et al., 2012).

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