OnLine Journal of Earth Sciences 8 (2): 31-40, 2014
ISSN: 1991-7708

Possibility for Identifying the New Subduction Zone from Ionospheric Anomaly for a Deep Earthquake (625.9 km) on 14 August, 2012, M = 7.7 near Poronaysk, Russia: Two-Dimensional Principal Component Analysis

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Abstract: Two-Dimensional Principal Component Analysis (2DPCA) has been performed to examine ionospheric Total Electron Content (TEC) data in order to detect TEC precursor for a deep earthquake occurred at 02: 59:42 on 14 August, 2012 (UTC) (M_w = 7.7) with its depth at 625.9 km near Poronaysk, Russia. The examined TEC data were during the time period from 00:00 on 09 August to 02:50 on 14 August, 2012 (UTC) which were 5 days before the earthquake because the ionospheric precursors usually revealed in such time period. A ionospheric TEC precursor with the more large principal eigenvalues of 2DPCA have been localized around the epicenter during the time period from 02:25-02:30 on 14 August, 2012 (UTC) and the duration time was at least 5 min. Ionizing radiation Radon gas release should be a possibility to cause the anomalous TEC fluctuation, e.g., electron density variation. If a mount of radiation radon which caused the TEC anomalies was trapped in the asthenosphere, then the asthenosphere should be very thick with deep bottom in this zone which belongs to the subduction zone between the Pacific plate and the North America. A zone that was previously unknown to be the subduction zone could now be identified as through earthquake-related TEC anomaly. Therefore in this study, not only TEC anomaly could be detected but also new plate boundary with subduction zone is possible to be found. However, if this very deep earthquake does indeed record inter-plate seismicity, then the asthenosphere in this region must have a large thickness.

Key words: Two-Dimensional Principal Component Analysis (2DPCA), Total Electron Content (TEC), precursor, subduction zone, Taiwan

INTRODUCTION

Recent studies have shown that the earthquake-associated Total Electron Content (TEC) anomalies were detectable using Principal Component Analysis (PCA) without considering non-earthquake TEC disturbance, e.g., geomagnetic storm activity (Lin, 2010, 2011a, b). Similarly, Nonlinear Principal Component Analysis (NLPCA) has been used to detect the TEC anomaly (Lin, 2012). The large principal eigen value of PCA and NLPCA indicated earthquake-associated TEC anomaly according to the statistical analysis of PCA (Lin, 2010). The previous results have shown that these procedures were sensitive to seismo-ionospheric effects.

In this study, 2-Dimensional Principal Component Analysis (2DPCA) is performed to detect TEC precursor related to an earthquake occurred at 02:59:42 on 14 August, 2012 (UTC) (M_w = 7.7) with the epicenter of (49.78°N, 145.13°E) near Poronaysk, Russia. The depth of this earthquake is 625.9 km (US Geological Survey). 2DPCA has different algorithm from the PCA and NLPCA. In the past studies, the PCA and NLPCA were applied to the TEC maps after image decoding of the map. However, after image decoding to the pixels' gray intensity as inputted matrix data of PCA and NLPCA, the wedge problem occurred with large loss of original information in the wedge of a map (Basnet, 2012). Such wedge problem influenced the precision of PCA and NLPCA, although the inputted matrix data were not the small sample size data (e.g., with the dimension of 612×317 pixels in some past researches). The small sample size data problem will be introduced in this study. The TEC data with low spatial resolution (will be small sample size data) which are not suitable to be processed with PCA and NLPCA are used by 2DPCA in order to avoid causing the small sample size data problem in this study.

TEC data are acquired from NASA Global Differential GPS System (GDGPS) (http://www.gdgps.net/products/tec-maps.html)(http://aiuws.unibe.ch/ionosphere/). Global ionospheric TEC map (GIM) is derived by using TEC data from ~100 real-time GDGPS tracking sites (http://www.gdgps.net/system-desc/images/world.png) augmented with additional sites that are available on 5 min basis (5 min-resolution). These sites can inquire not only TEC satiation of surrounding regions but also TEC situation of distant regions. The integrated electron density data along each receiver-GPS satellite link is processed through a Kalman filter in a sun-fixed frame to produce the GIM and TEC data. It is worth mentioning that TEC data are estimated TEC values in this study. When estimating TEC value, some biases during restore of TEC values from measurements of dual-frequency delays of GPS signals, e.g., resolving of carrier phase ambiguity, determination hardware delays for phase, code measurements, tropospheric and multipath problems are necessary to be corrected. The Kalman filter has been widely performed to estimate the TEC value with less bias. The Kalman filter is used to removed the biases. Therefore, temporal and spatial discrimination has influences for compensation and such influences could be endured. The detailed explanations are given in the US-TEC Technical Document (2004) (http://www.swpc.noaa.gov/ustec). Finally, the estimated TEC data could be optimized to represent the true TEC situation of the global region (Kechine *et al*., 2004; Ouyang *et al*., 2008; Spencer, 2004). The TEC data during the time period from 00:00 on 9 August to 02:50 on 14 August, 2012 (UTC) which are 5 days before the earthquake, are examined by using 2DPCA because the ionospheric TEC precursors usually revealed in such time period (Liu *et al*., 2006). The GIMs during the examined time period are the roles to observe TEC situation not to be processed.

MATERIALS AND METHODS

2DPCA: 2DPCA is a procedure for a two-dimensional data from. Let the data be represented by a matrix F with the dimension of a×b. The linear projection of the matrix F is considered as follows (Sanguansat, 2012).

$$y = Fx \tag{1}$$

Where:

x = Projection axis with the dimension of n×1
y = The projected feature with dimension of a×1 of this data on z called principal component vector
E = Mean of the elements of vector

$$Vx = (y - Ey)(y - Ey)^T \tag{2}$$

Where:

$$tr(Vx) = tr\{x^T Zx\}$$
$$Z = (F - EF)(F - EF)^T \tag{3}$$

The vector x maximizing Eq. 3 corresponds to the largest (principal) eigen value of Vx which represented the main characteristics of the data related to the largest (principal) component in the 2DPCA domain (Kong *et al*., 2005; Sanguansat, 2012). The matrix Vx is called covariance matrix for 2DPCA. For PCA and NLPCA, one-dimension TEC data is reshaped to two-dimension TEC data and reshaping caused loss of information (Kramer, 1991) due to Small Sample Size (SSS) after reshaping to a small matrix. However, the 2DPCA can be used to small matrix (Kong *et al*., 2005).

TEC data processing using 2DPCA: The TEC data are processed during the time period from 00:00 on 9 August to 02: 50 on 14 August, 2012 (UTC) before the earthquake. The resolution of the TEC data for the GDGPS system is 5 and 2.5° in latitude and longitude, respectively (Hernandez-Pajares *et al*., 2009). The global TEC data during the examined time period are divided into 600 smaller areas 12° in longitude and 9° in latitude, respectively. Each smaller area includes at least 4 TEC data and thus 4 TEC data are taken to analyze. The 4 TEC data form a matrix F of dimensions 2×2 in Eq. 1. The matrix belongs to the SSS data. Only a TEC precursor is detected during the time period from 02:20-02:35 (UTC) on 14 August, 2012 after TEC data processing. Therefore, the procedure of TEC data processing during this time period in Fig. 1 is represented in the study.

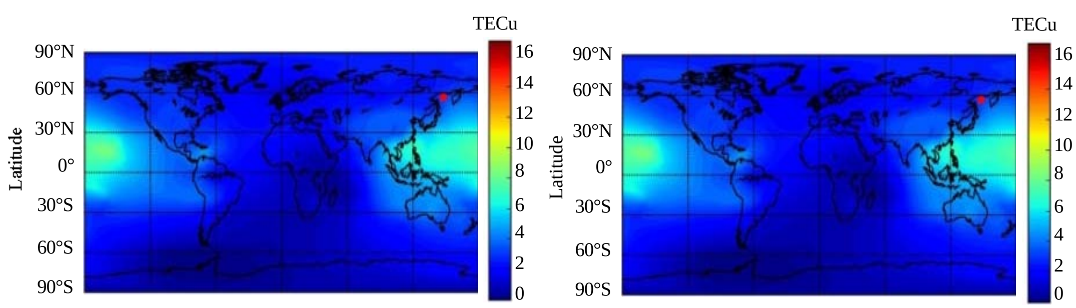

Fig. 1: Continue

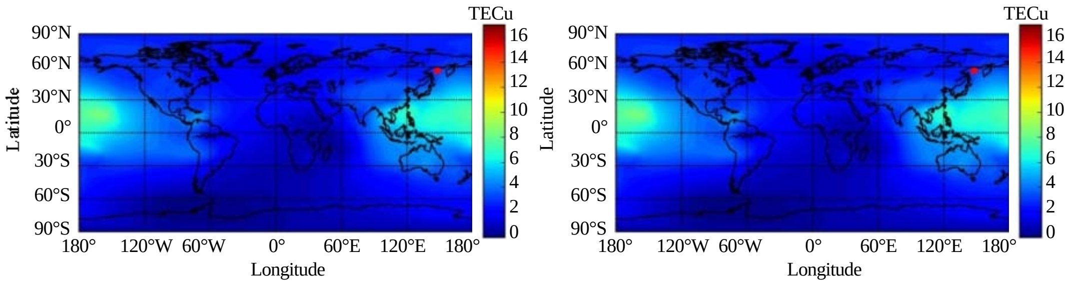

Fig. 1: The GIMs during the time period from 02:20-02:35 on 14 August, 2012 (UTC). The red spot in each GIM represents the location of the earthquake epicenter

RESULTS AND DISCUSSION

Figure 2 gives a color-coded scale of the magnitudes of principal eigenvalues of 2DPCA corresponding to Fig. 1. Color intensity denotes magnitude of eigen value and it can be shown that 600 principal eigen values are assigned. Representative of large principal eigenvalues in this shows the existence of a TEC precursor with a large principal eigen value given nearby the region of this large earthquake. A TEC precursor reveals by the large principal eigen value during the time period from 2:25-2:30 (UTC) on 14 August, 2012. Figure 3 shows the Kp indices from 7-15 August, 2012 (UTC) which are relatively small indicating (≤4), so that the geomagnetic activity could not be responsible for the TEC anomaly for this time period.

Analysis of TEC data for other time period: 2DPCA is applied to the TEC data in Fig. 4 by using the same data processing method during the time period from 02:20-02:35 (UTC) on 7 August, 2012 for comparison with the previous results. The principal eigenvalues of 2DPCA are shown in Fig. 5. Figure 6 shows the GIMs during the time period from 02:20-02:35 (UTC) on 15 August, 2012. Corresponding principal eigen values of 2DPCA are shown in Fig. 7. The time period (7-15 August) was geomagnetic quiet time according to Fig. 3. Similar TEC anomaly is not detected. Such 2 days were selected to compare with the TEC situation on 14 August because the space weather was similar to 14 August, 2012 and they were the time near the day on 14 August, so that the non-earthquake TEC background noises were similar. The analysis results support the TEC anomaly on 14 August should be associated with the earthquake.

Examining of credibility using 2DPCA Related to another earthquake: To confirm credibility of 2DPCA, the TEC data of FORMOSAT-3 satellite system used by Lin (2011b) during the time period from 20:00 to 22:00 (UTC) on 8, 11 and 12 June, 2008 for Japan' Iwate-Miyagi Nairiku earthquake occurred at 23:43:00 on 13 June, 2008 (UTC) (M_w = 6.9) with the epicenter of (39.02°N, 140.53°E) are again examined using 2DPCA. The 6 TEC data in each area (36° in longitude and 18° in latitude, respectively) showing the inputted matrix C in Eq. 1 (dimensions 2×3) belongs to SSS data. Figure 8 shows the magnitudes of principal eigenvalues of 2DPCA. Results show that the 2DPCA is more credible and accurate than PCA and more clear TEC anomalies related to Japan' Iwate-Miyagi Nairiku earthquake are apparent (2011b) because in the Lin (2011b)'s research, the TEC data were reshaped into a matrix from one-dimension.

Analysis of TEC data during a geomagnetic storm: The day on 15 July, 2012 (UTC) underwent a geomagnetic storm according to the Kp indices during the time period from 14-16 July, 2012 (UTC) shown in Fig. 9 (the Kp indices ≥4 on 15 July). The duration time of this geomagnetic storm is at least 1 day. 2DPCA is applied to the TEC data (Fig. 10) during the time period from 05:00-06:00 on 15 July, 2012 (UTC) with the same TEC data processing method. The examined time period (1 h duration) should be enough large to become aware of apparent variances of this geomagnetic storm. This storm may affect observation of EIA, so that EIA is not obvious. The results of 2DPCA are represented with the magnitude of principal eigenvalues being smaller shown in Fig. 11. Even, a geomagnetic storm activity on the ionosphere did not produce the same level of large principal eigen values returned by 2DPCA for TEC anomalies related to large earthquake. Therefore, the 2DPCA is suitable to detect earthquake-associated TEC anomaly regardless of the geomagnetic storm activity.

2DPCA was able to detect a TEC precursor of an earthquake near Poronaysk, Russia. The precursor has been found during the time period from 02:25-02:30 (UTC) on 14 August, 2012 and the duration time was at least 5 min. TEC precursor was not detectable in other examined time period. In the past studies, two clear earthquake-associated TEC anomalies before and after

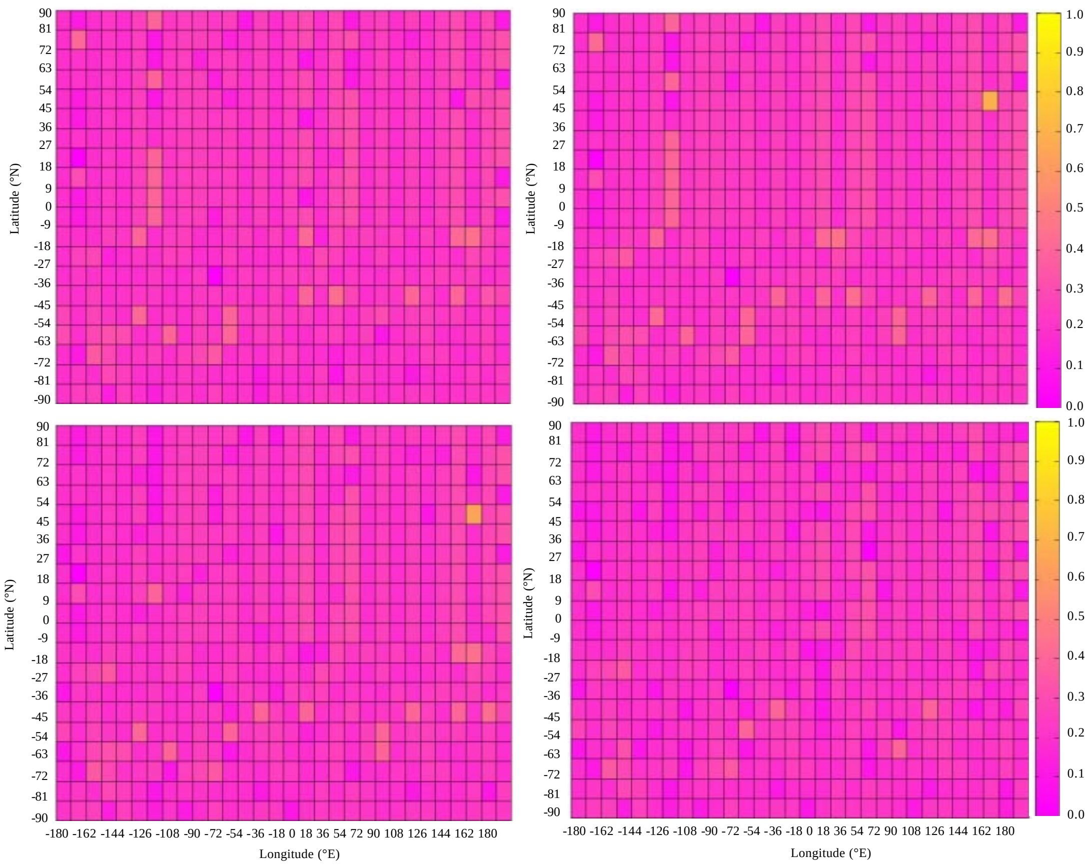

Fig. 2: Color-coded scale of the magnitudes of principal eigenvalues corresponding to Fig. 1 with 2DPCA. The color within a area denotes the magnitude of a principal eigenvalue corresponding to Fig. 1, so that there are 600 principal eigen values assigned for 600 areas in each small map, respectively. The earthquake-related TEC anomalies are represented with large principal eigenvalues during the time period from 02:25-2:30 (UTC)

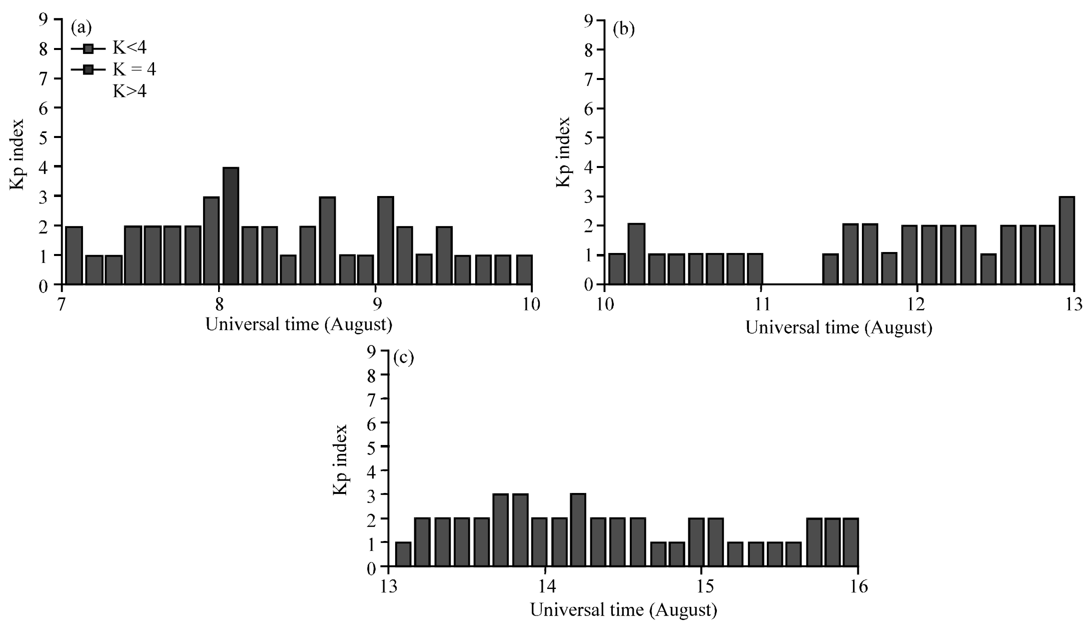

Fig. 3: The Kp indices during the time period from 7-15 August, 2012 (UTC) (space weather prediction center)

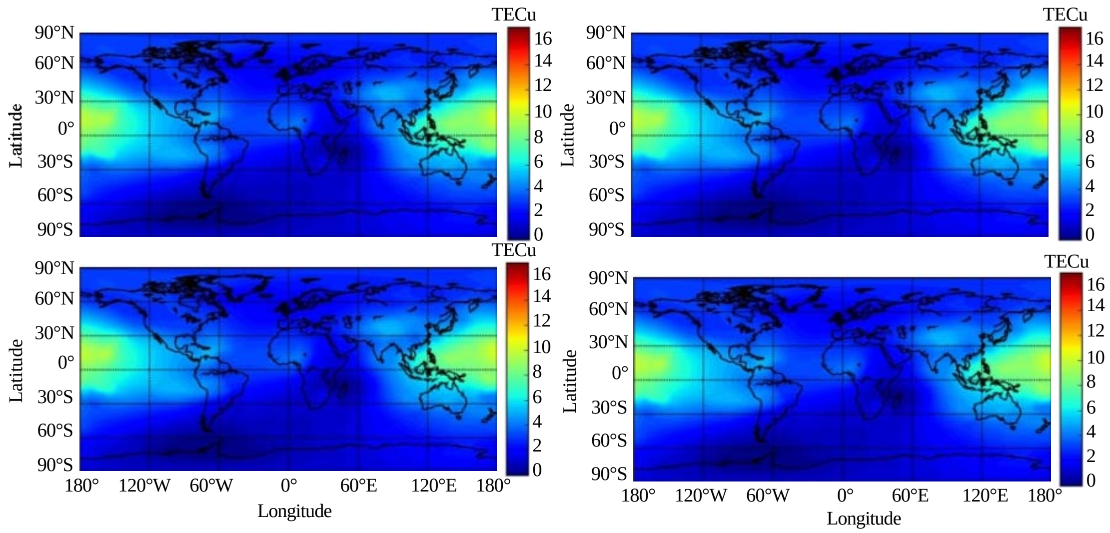

Fig. 4: The GIM during the time period from 02:20-02:35 (UTC) on 07 August, 2012

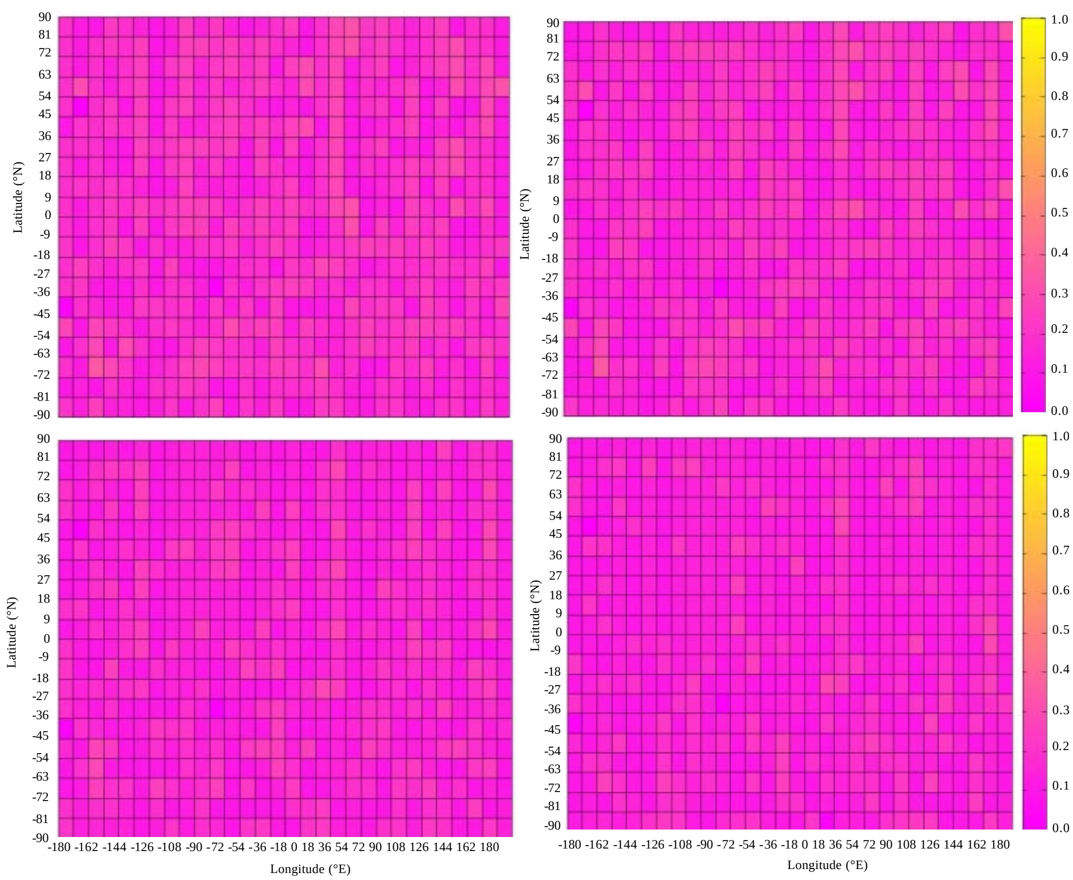

Fig. 5: A color-coded scale of the magnitudes of principal eigen values related to Fig. 4 (02:20-02:35 UT)

China's Wenchuan earthquake of 12 May, 2008 (UTC) (M_w = 7.9) have been identified using one-dimensional PCA (Lin 2011a, 2012, 2013). However, the Wenchuan earthquake was not a deep earthquake. 2DPCA had also the ability to detect clear TEC anomaly related to this deep earthquake not only for shallow earthquakes. This study

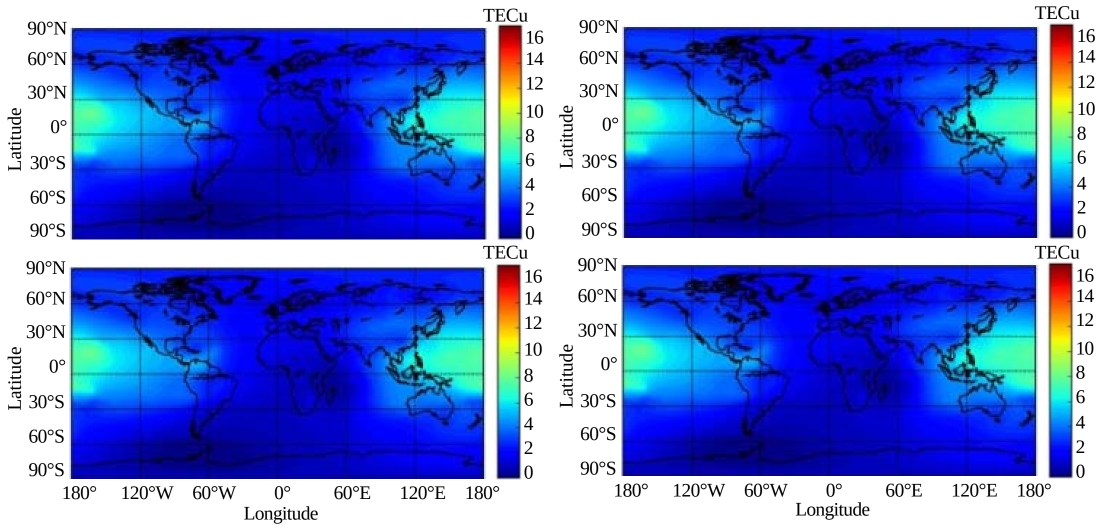

Fig. 6: The GIMs during the time period from 02:20-02:35 on 15 August, 2012 (UTC)

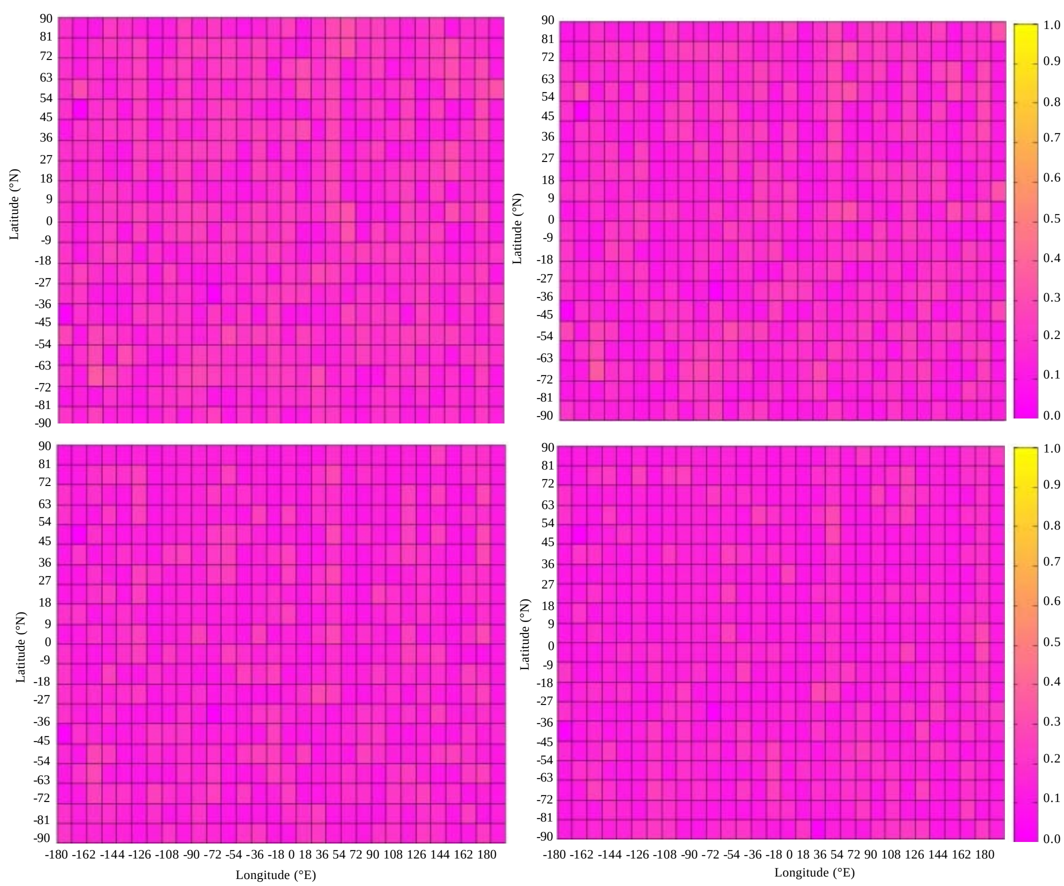

Fig. 7: A color-coded scale of the magnitudes of principal eigen values related to Fig. 6 (02:20-02:35 UT)

has confirmed the reasonability and credibility of 2DPCA. Accordingly, studies of TEC disturbance suggest three possible explanations for earthquake associated anomalies. First possibility is shock waves (gravity waves) (Jin *et al*., 2010). It should be likely those acoustic shock waves from topside vibrations would be

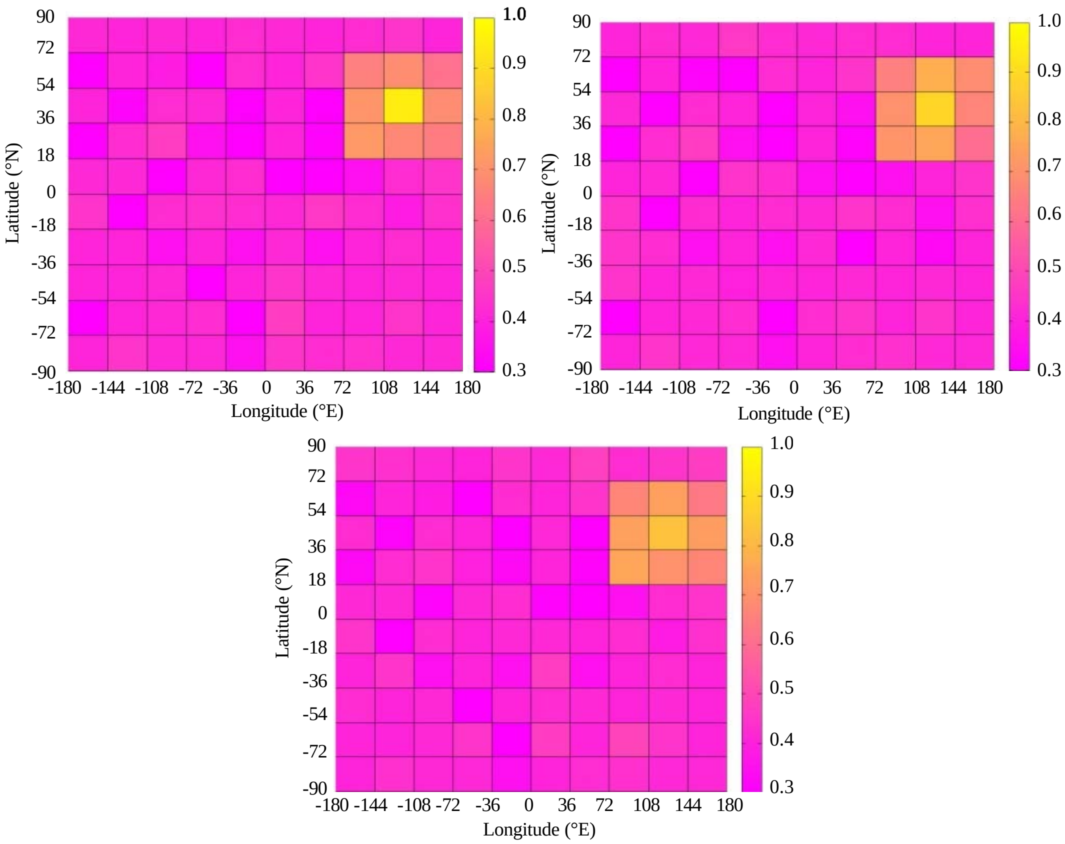

Fig. 8: A color-coded scale of the magnitudes of 100 principal eigen values of 2DPCA for the GIMs during the time period from 20:00-22:00 on 8, 11 and 12 June, 2008 (UTC) (Lin, 2011b). The earthquake-associated TEC anomalies are represented by large principal eigen values

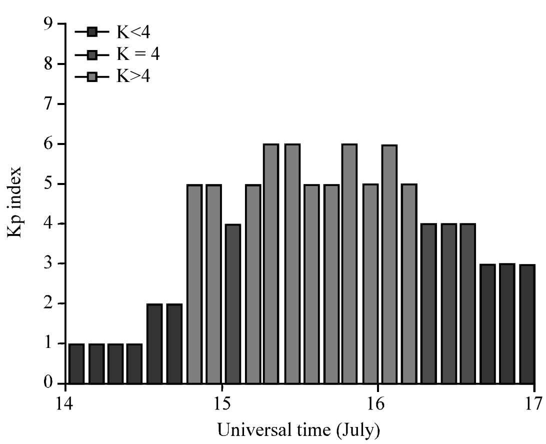

Fig. 9: The Kp indices during the time period from 14-16 July, 2012 (UTC) (space weather prediction center)

responsible for the TEC anomaly since the earthquake was deep. The second possibility is the presence of an electric field creating large scale ionospheric density irregularities due to stress variance in rocks near the focus of the earthquake (Pulinets, 2004; Freund, 2003). An electric field would not be able to travel to the ground surface from 625.9 km down. The third possibility is that Radon gas release, on the other hand, could occur through micro-cracks formed in the crust and the earth surface. Radon gas can lead to lower atmospheric electric fields and these can travel unimpeded into the ionosphere along geomagnetic lines (Pulinets, 2004). This seems like the most reasonable explanation for the earthquake-related TEC anomaly. The Radon gas release from the focus should cause the anomaly TEC gradients or fluctuations. However, could the radon gas undergo the high temperature which was trapped in the asthenosphere to cause the TEC anomalies? It is possible because the gas belongs to the inert gas. Usually for such geomathematical problem whether 2DPCA is valid, it must to suffer the theoretical and experimental verification. VAN group (Varotsos, Caesar Alexopoulos and Kostas Nomikos) and some researchers (Varotsos and Alexopoulos, 1984a, b; Varotsos *et al*., 1988, 1993;

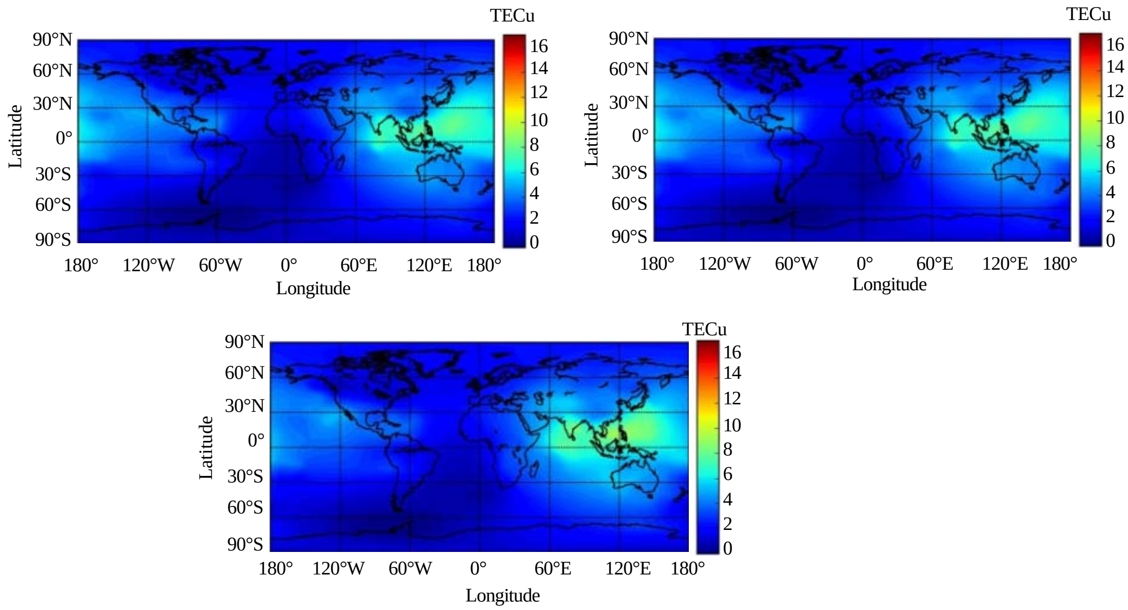

Fig. 10: The GIM during the time period from 05:00-06:00 on 15 July, 2012 (UTC)

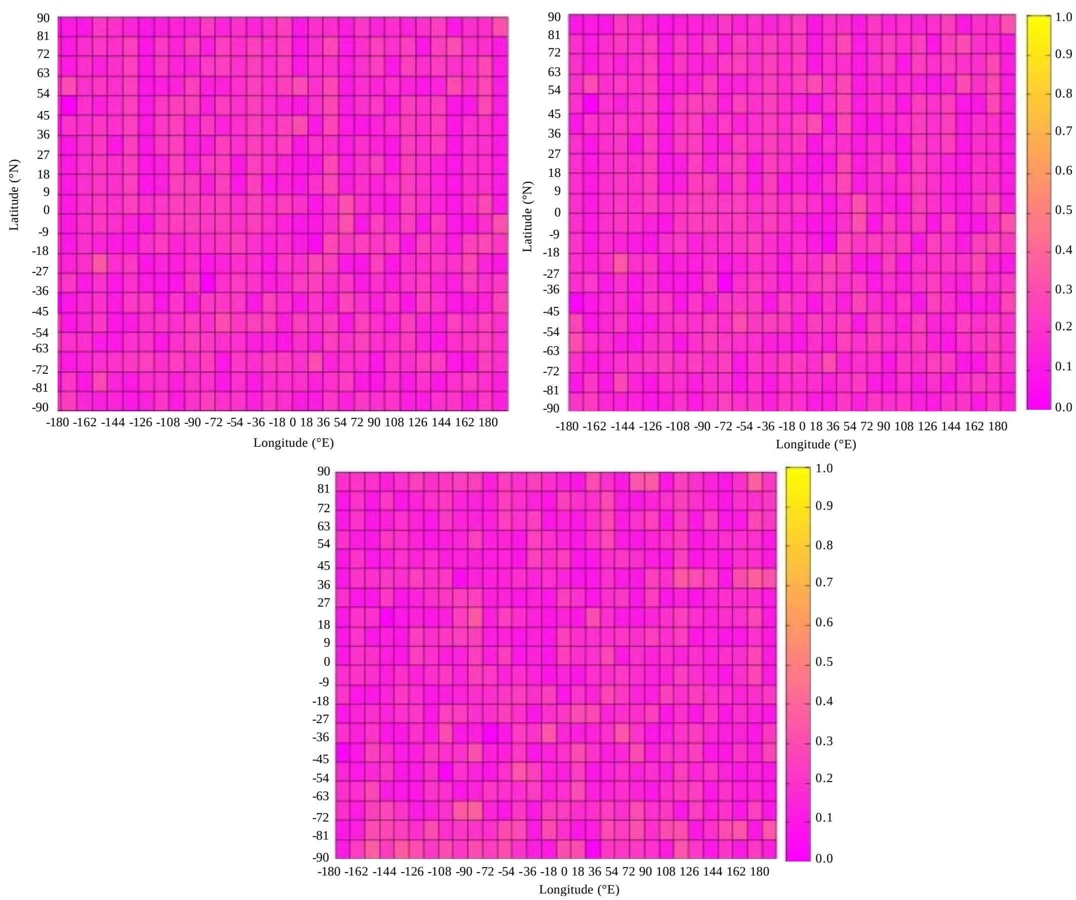

Fig. 11: A color-coded scale of the magnitudes of principal eigenvalues related to Fig. 10 (05:00-06:00 UT)

Pulinets *et al*., 2003; Freund, 2003; Pulinets and Boyarchuk, 2004) have done the theoretical and experimental verification for their problems. However, the verifications of these researchers were suitable for shallow earthquakes.

In this study, the 2DPCA should have already theoretical verification. Remind, as stated previously, a principal eigen value of 2DPCA represented the TEC situation of an area (grid). The lager principal eigen value of an area revealed the large TEC difference from other areas shown in Fig. 2. It should have been confirmed the theoretical verification. Radon radiation might exist in the asthenosphere through the information of such deep earthquake. If it is true, then the asthenosphere should be very deep. This earthquake let the Pacific plate move towards the West-Northwest with respect to the North America plate. The plate boundary here is sometimes divided into several microplates that together define the relative motions between the larger Pacific, North America and Eurasia plates, including the Okhotsk and Amur microplates that are respectively part of North America and Eurasia. A zone that was previously unknown to be the subduction zone could now be identified as that through a TEC anomaly related to a deep earthquake, whereas large shallow earthquakes are usually categorized as inter-plate earthquakes, such as the 2008 Wenchuan earthquake that occurred in China. Radon is one of several inert gases that can remain stable up to very high temperature conditions in the earth.

Consequently, deep-seated radon may have been released from the earthquake focal region and subsequently caused the observed TEC anomaly in the ionosphere. Thus, it is possible that previously unidentified plate boundaries could be detected by correlating seismic station wave signals, assuming that they can be recorded and anomalous TEC fluctuations. This is possible due to very deep earthquakes usually occurring at plate boundaries rather than in inter-plate settings. If inter-plate seismicity occurs at great depth, the focus should be located in the asthenosphere which may be thick. However, it should be noted that seismic activity may cause radon to be released from a region within the earth other than the earthquake focus (not caused by earthquake) which may still result in a TEC anomaly being observed at the surface. As a result, if radon is identified at the earth's surface before or after a seismic event, care must be taken to determine the true source of the emission. The duration of the observed TEC fluctuation, interpreted to have been caused by the release of ionizing, radon gas is very short. This rapid subsidence may have been due to either the plasma having had a large damping at that time, the ionizing radon gas having been released over a short timescale or that some radon isotopes have a very short half-life and will rapidly decay away.

CONCLUSION

A TEC precursor has been detected during the time period from 02:25-02:30 on 14 August, 2012 (UTC) before a deep (625.9 km) earthquake occurred at 02: 59:42 on 14 August, 2012 (UTC) near Poronaysk, Russia with the duration time being at least 5 min. Ionizing radiation radon gas release from asthenosphere was a possible reason to cause the TEC anomalous TEC fluctuations, e.g., electron density variation. The bottom of asthenosphere was very deep in this region which belongs to a subduction zone. The asthenosphere should be very thick. However as stated previous, the radon related to earthquake is not easy to identify. However if radon can be detectable related to an earthquake, then this technique could be useful for understanding of the physical coupling between the ionosphere and processes on the ground and at lower altitudes due to ionizing radiation radon gas release and the large principal eigen value had a physical meaning and is not a mathematical index.

ACKNOWLEDGEMENTS

The researchers is grateful to NASA Global Differential GPS system (GDGPS) and Space Weather Prediction Center for the useful references Data.

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