RESEARCH PAPER

Ionospheric anomaly at the occurring time of China’s May 12, 2008, M = 7.9 Wenchuan Earthquake using nonlinear principal component analyses and image decoding

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Abstract Nonlinear principal component analysis (NLPCA) and image decoding are used to determine the spatial pattern of a total electron content (TEC) map anomaly in the ionosphere above China’s Wenchuan earthquake of 12 May, 2008 (UT) ($M_o = 7.9$). The earthquake occurred at 06:28:01UT and the time period examined using NLPCA is 06:00 to 08:00UT. The TEC map of previous time period is transformed to an input matrix of NLPCA using image decoding, and then the TEC anomaly found is widespread and less intense at an altitude of 200 km using NLPCA; however, it becomes more intense and localized with height up to an altitude of 300 km. This paper discusses potential causes of the anomaly with emphasis on very rising acoustic shockwaves and snow-plow effects on ionospheric electron plasma resulting from the mainshock of the earthquake.

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1. Introduction

Anomalies in ionospheric total electron content (TEC) associated with large earthquakes have been widely researched both as precursors and aftereffects (Artru and Lognonné, 2001; Garcia et al., 2005; Hegai et al., 2006; Liu et al., 2006, 2008, 2009; Lognonné et al., 2006; Marchand and Berthelier, 2008; Pulinets et al., 2000, 2007; Pulinets, 2004; Singh et al., 2010; Zhao et al., 2008). There are many possibilities including gravity waves generated by the solid-earth and sea, as well as lower atmospheric electric fields resulting from earthquake preparation processes that can be transferred into the ionosphere along geomagnetic lines (Pulinets, 2004). Post earthquake TEC anomalies are less controversial as it is well known that TEC disturbance is associated with great earthquakes, volcanic activity, meteor strikes, and anthropogenic activity. These TEC anomalies are most likely caused by the acoustic gravity wave traveling from the earth’s surface into the ionosphere. The mechanism for this is thought to be the earth’s atmosphere acting as a natural amplifier. During an earthquake tiny amounts of kinetic energy are transferred from the solid earth
to the lower atmosphere. If this kinetic energy is conserved, then given the exponential decline in atmospheric density with height, waves of great amplitude can result in the ionosphere. It has been estimated that millimeter disturbances at the earth’s surface can be amplified to waves of amplitude 100 m at 100 km altitude (Artru and Lognonné, 2001; Lognonné et al., 2006).

A study by Lognonné et al. (2006) using ground based GPS receivers to detect post-seismic ionospheric disturbance found that the measurable impact of Rayleigh waves resulting from the Nov. 3, Denali, Alaska $M = 7.9$ earthquake produced small but detectable changes in the TECu (10$^{16}$ electrons/m$^2$ = 1 TECu) count of 0.1% peak to peak. This disturbance was detected by 6 other satellites. Lognonné et al. (2006) also measured the effects of near field seismic waves for the Hokkaido Tōhoku – Oki earthquake of Sept. 25, 2003. In that experiment, they found that acoustic waves could be detected as high as 800 km, they also measured the Rayleigh-wave impact for the same earthquake and got similar results to those for the Alaskan Denali earthquake in terms of TECu disturbance. One issue, however, with all TEC measurements is the nature of the ionosphere. The electron content of the ionosphere is highly dynamic plasma so that establishing anomalies and event association is not easy. For example, determining a running median of TEC content before large earthquakes to search for precusor TEC anomalies is difficult and may not always be reliable because TEC can be affected by many factors. However, recent studies have shown that earthquake-associated TEC anomalies are detectable using principal component analysis (PCA) (Londoño et al., 2005; Sanguansat, 2012) (Lin, 2010b, 2011).

PCA is an alternative pure mathematical method for measuring TEC anomalies. The method relies on exploiting signal delay between global positioning system (GPS) satellites and ground receiver stations without direct observation of ionospheric TEC. The long-term period variance of ionospheric TEC (Fig. 17 Lin (2010a)) does not affect the outcome of the results using PCA and the potential influence of other factors such as solar flares and geomagnetic disturbance are eliminated using relevant $P_{DA}$ and $K_p$ indexes. While these PCA experiments were able to detect and even describe the physical shape of earthquake-associated TEC anomalies, the PCA method might not be as useful as nonlinear principal component analysis (NLPCA) in the detection of TEC anomalies. NLPCA is an augmented version of PCA that can cover non-linear behaviors of data.

The goal of this paper is to examine the spatial disturbance of ionospheric TEC associated with the 12 May 2008 Wenchuan earthquake using NLPCA and discuss possible causes of any discovered anomaly. The Wenchuan earthquake occurred at 06:28:01(UT) on 12 May 2008, it is expected that in the period 6:00 to 8:00 UT the behavior of the ionosphere will be complicated showing more nonlinearity during this time due to the stark effects of the main shock. For comparison, NLPCA and PCA are applied to ionospheric TEC maps at heights ranging from 150 to 450 km to identify and examine any earthquake-associated TEC anomalies between 6:00 and 8:00 UT. Data for the experiments come from Integrated Electron Content data of the FORMOSAT-3 satellite system. The FORMOSAT-3 system can provide 2500 GPS-occultation daily average distributed datasets updated every 90 min, and GPS TEC data from International GPS Service for Geodynamics (IGS), which is a network of GPS receiver sites; therefore, the TEC data are meaningful to research in this paper. After completing both PCA and NLPCA, comparisons are made for solar and geomagnetic activity during this time period.

2. Method

2.1. PCA and NLPCA

PCA is a widely used technique in data analysis (Londoño et al., 2005; Sanguansat, 2012). It is a simple method that allows the extraction of relevant information from multivariate datasets. PCA is used to identify and remove correlations among problems variables so as to reduce dimensional space and uncover linear correlations between variables in a given dataset. NLPCA, on the other hand, can cover nonlinear behaviors; for example, the nonlinear dynamics of ionospheric plasma.

Mathematically, for PCA the input matrix $X$ which has the dimensions $n \times m$; $S$ is the scores matrix and has dimensions $n \times r$, where $r$ is the given number of factors; $R$ is called the loading matrix and it has dimensions $m \times r$ ($m > r$); and the matrix of residuals is called $E$ with dimensions $n \times m$ (Kramer, 1991).

The scores matrix is given by the following relation:

$$S = SP^T + E$$

(1)

taking $P^T P = I$ as the unit matrix for mapping a gaseous form:

$$S = XR$$

(2)

where $S$ is a row of $S$ (a single data vector), and $X$ is the corresponding row of $X$ or the coordinates of $S$ in the feature space. $R$ is the matrix for linear transformation. By reversing the projection, we get:

$$X' = SR^T$$

(3)

where $X' = X - E$ is the reconstructed measurement vector, and the Euclidean norm is $||E||$, which must be minimized for the given number of factors. To satisfy this criterion the columns of $R$ must be the eigenvector corresponding to the $r$ eigenvalues of covariance matrix of $X$ when computed.

For NLPCA, by analogy to Eq. (2), mapping is in the form:

$$S = H(X)$$

(4)

where $H$ is a nonlinear vector function with $r$ individual nonlinear functions: $H = \{H_1, H_2, \ldots, H_r\}$

By analogy to Eq. (3):

$$X' = G(S)$$

(5)

where $G$ is the second nonlinear vector function with $m$ individual nonlinear functions: $G = \{G_1, G_2, \ldots, G_m\}$, the loss of information is again measured by $E = X - X'$ to minimize $||E||$, as with PCA, when $H$ and $G$ are selected. Similar to PCA, the largest eigenvalues of the covariance matrix $X$ can then be computed. The largest eigenvalue is called the principal eigenvalue that represents the main characteristics of input signals $X$.

2.2. TEC processing

The global ionospheric maps (GIM) of Figs. 1a–6a in the time period 06:00–08:00 UT on 12 May 2008 are divided into 100 smaller grids 36° in longitude and 18° in latitude.
Each grid has dimensions 216 pixel \times 424 pixel, which is decoded from RGB mode into Gray-scale mode to form the input matrix $X$ of dimensions $216 \times 424$ of Eq. (4) through image decoding with the pixel gray intensity corresponding to the color of unit bar (Lin, 2010b, 2011; Vasilescu and Terzopoulos, 2007; Zhang et al., 2009). This allows for principal eigenvalues to be computed for each of the 100 smaller grids using NLPCA. NLPCA is used and the respective results are given in Figs. 1b–6b that show the principal eigenvalues using TEC data $X$ as inputs in Eq. (2) of PCA. No clear large principal eigenvalues are found in this figure using PCA. Large principal eigenvalues are defined as principal eigenvalues larger than 0.5 in a normalized set (Lin, 2010a). This figure gives a color-coded scale of the magnitudes of principal eigenvalues corresponding to Fig. 1a. The color within a grid denotes the magnitude of a principal eigenvalue corresponding to Fig. 1a, so that there are 100 principal eigenvalues assigned (i.e., each grid in the bottom figures represents a principal eigenvalue), respectively. The earthquake-related TEC anomalies are represented using large principal eigenvalues (i.e., principal eigenvalues $> 0.5$ in a normalized set) (Lin, 2010a).

For NLPCA, Fig. 1a shows the GIM on 12 May for 06:00–08:00 UT. Fig. 1b gives a color-coded scale of the magnitudes of principal eigenvalues corresponding to Fig. 1a. Color intensity denotes magnitude. From the figure it can be seen that 100 principal eigenvalues are assigned (i.e., each grid in the bottom figures represents a principal eigenvalue). Figs. 2a–6b show the same approach but for different heights. Varying color intensity, representative of large principal eigenvalues in the Figs. 1b–6b, shows the existence of TEC anomalies with large principal eigenvalues over the region of the Wenchuan earthquake. At lower altitudes the TEC anomaly distributes over a wide area from a height of 200–250 km (Fig. 2b). The distribution range of the anomaly reduces with height; intensity, however, increases. At a height of 250–300 km (Fig. 3b), very

3. Results

For NLPCA, Fig. 1a shows the GIM on 12 May for 06:00–08:00 UT. Fig. 1b gives a color-coded scale of the magnitudes of principal eigenvalues corresponding to Fig. 1a. Color intensity denotes magnitude. From the figure it can be seen that 100 principal eigenvalues are assigned (i.e., each grid in the bottom figures represents a principal eigenvalue). Figs. 2a–6b show the same approach but for different heights. Varying color intensity, representative of large principal eigenvalues in the Figs. 1b–6b, shows the existence of TEC anomalies with large principal eigenvalues over the region of the Wenchuan earthquake. At lower altitudes the TEC anomaly distributes over a wide area from a height of 200–250 km (Fig. 2b). The distribution range of the anomaly reduces with height; intensity, however, increases. At a height of 250–300 km (Fig. 3b), very
large principal eigenvalues are given. As height increases the range continues to decline along with the intensity of large principle eigenvalues. However, no anomaly is found using PCA as shown in Figs. 7a–7f.

The possibility of other factors such as a solar flare and geomagnetic effects affecting the results is considered by examining $D_s$ and $K_p$ indexes (Elsner and Kavlakov, 2001; Hamilton et al., 1986; Mukherjee, 1999) in Figs. 8a and 8b, respectively. The $D_s$ index is a geomagnetic index which monitors world-wide magnetic storm levels based on the average horizontal component of the geomagnetic field from mid-latitude and equatorial magnetograms (Note: Magnetic storms are indicated by negative $D_s$ values whereby the more negative the $D_s$ the more intense the magnetic storm). Fig. 8a shows that for May the $D_s$ index was relatively flat indicating that geomagnetic storm activity could not have been responsible for the TEC anomaly. The $K_p$ index shown in Fig. 8b is calculated as a weighted average of K-indexes from a network of

Figure 3b  The figure gives a color-coded scale of the magnitudes of principal eigenvalues related to Fig. 3a.

Figure 4a  This figure shows the GIM (unit: TECu) on 12 May at height 300–350 km for time 06:00–08:00UT.

Figure 5a  This figure shows the GIM (unit: TECu) on 12 May at height 350–400 km for time 06:00–08:00UT.

Figure 5b  The figure gives a color-coded scale of the magnitudes of principal eigenvalues related to Fig. 5a.

Figure 6a  This figure shows the GIM (unit: TECu) on 12 May at height 400–450 km in the time 06:0008:00UT.
geomagnetic observatories (Note: The $K_p$ index allows for disturbances in the horizontal component of the earth’s magnetic field to be represented on a scale of 0–9 with 1 being calm and 5 or more indicating a geomagnetic storm). According to Figs. 8a and 8b, the geomagnetic storm activity was low during the examined time period (Muella et al., 2009; Plotnikov and Barkova, 2007; Uyeda et al., 2009).

4. Analysis of NLPCA during large geomagnetic storm

To get a clear understanding of the relative effects of geomagnetic storm and solar flare activity on the outcomes of NLPCA applied to ionospheric TEC in the discovery of earthquake-related TEC anomalies, NLPCA is applied to a day with a known consequent geomagnetic storm. This experiment will provide principal eigenvalues for TEC anomalies under geomagnetic conditions and these principal eigenvalues can be used for comparison with principal eigenvalues given by NLPCA analysis of the Wenchuan earthquake. On August 04 a powerful almost X-class solar flare was

![Figure 6b](image) The figure gives a color-coded scale of the magnitudes of principal eigenvalues related to Fig. 6a.

![Figure 7a](image) The figure gives a color-coded scale of the magnitudes of principal eigenvalues using PCA related to Fig. 1a.

![Figure 7b](image) The figure gives a color-coded scale of the magnitudes of principal eigenvalues using PCA related to Fig. 2a.

![Figure 7c](image) The figure gives a color-coded scale of the magnitudes of principal eigenvalues using PCA related to Fig. 3a.

![Figure 7d](image) The figure gives a color-coded scale of the magnitudes of principal eigenvalues using PCA related to Fig. 4a.
recorded from sunspot 1261. This was followed by a related geomagnetic storm (Fig. 9. \(D_s\) index for 06 August 2011) prompted by a fluctuation in the solar wind. The GIMs (Figs. 10a–14a) from 00:00 to 4:00 UT at a time interval of 1 h on 06 August 2011 are processed using NLPCA with same data processing described in Section 2.2 (Data source: NASA Global Differential GPS system (GDGPS), the core of which is the NASA Global GPS Network (GGN)). The results are represented in Figs. 10b–14b with the magnitude of principal eigenvalues being less than 0.5 in a normalized set (Lin 2010a). If we compare this result with those for Figs. 1b–6b (same scale) for the Wenchuan earthquake analysis, we can see that even a large solar flare’s influence on the ionosphere did not produce the same level of large principal eigenvalues returned by NLPCA for TEC anomalies over the Wenchuan earthquake epicenter. This is a strong indication that NLPCA is suitable for detecting earthquake-associated TEC anomalies for large earthquakes.

5. Discussion

In this study, NLPCA was able to detect a TEC anomaly over the epicenter of the 12 May 2008 Wenchuan earthquake in the period 06:00 to 08:00 UT. The Wenchuan earthquake occurred at 06:28:01UT. Other earthquake-associated TEC anomalies have been identified for this earthquake using PCA for other time periods (Lin, 2010b, 2011), which should improve the statistical relevance of a discovery by NLPCA during the time
period 06:00 to 08:00 UT. However, PCA was not able to detect TEC anomaly for the period 06:00 to 08:00 UT while NLPCA was able to detect a TEC anomaly due to non-linear behavior of ionospheric plasma as stated in Section 2.1.

Identifying the precise cause of earthquake related TEC anomalies is not easy. One reason for this is the number of potential causes of earthquake related TEC anomalies that arise during earthquake preparation, the mainshock, and aftershocks. For example during the earthquake preparation phase, Pulinets and Boyarchuk (2004) suggest that radon emanating from active faults and cracks before earthquakes ionizes the near ground atmosphere to produce large vertical electric fields. Freund (2000) proposed that mobile positive holes in the earth’s crust could be activated by low-energy impact, sound waves, and fractures, creating charge clouds that could explain electromagnetic activity. Gravity waves arising from fine vibrations in the earth’s surface leading to gas release are another possibility. This results in lower atmospheric
turbulence and eventual ionospheric perturbations (Molchanov and Hayakawa, 1998). However, once an earthquake has occurred then the most evident physical mechanism is ground motion and fine surface vibrations. This is the possibility described in the introduction to this paper whereby acoustic shockwaves caused by vibrations at the earth’s surface are amplified through the atmosphere to affect TEC in the ionosphere above the earthquake zone.

If we assume that NLPCA was accurately able to describe the shape of the earthquake associated anomaly on this occasion, it is worth considering what its shape might tell us about its cause. The noted anomaly in this study begins at an altitude of 150–200 km and extends as high as 300 km where it is most intense. This is the F-region of the ionosphere. Accordingly, studies of electromagnetic disturbance suggest two possible explanations for earthquake associated anomalies at this altitude. One is acoustic gravity waves caused by Joule heating (Hegai et al., 1997) and the other is the presence of an electric field creating large scale ionospheric density irregularities (Liu et al., 2004; Pulinets and Legen’ka, 2003) coupled with potential drift of the anomaly toward the equator. However, the conical shape of this anomaly resembles what one would expect from rising acoustic gravity waves. As discussed in the introduction the earth’s atmosphere can act as a natural amplifier due to declining atmospheric density with height. A large earthquake, such as the May 12 2008 Wenchuan earthquake, is characterized by many fine vibrations at the earth’s surface which could produce a vertical acoustic pressure wave of great amplitude by the time it reaches the ionosphere. In the case of the Wenchuan earthquake, at a height of 200 km the TEC anomaly was widespread but less intense; however, it became more localized and intense at an altitude of 300 km. Such a description could possibly represent the stark and concentrated energy of an acoustic shockwave being formed in the lower atmosphere after the Wenchuan earthquake (Jin et al., 2010; Liu et al., 2010) traveling up into the ionosphere, and snow-plow effects on plasma with nonuniform density near the epicenter being caused by a very high acoustic shockwave velocity (Fruchtman, 1992), and the acoustic shockwave is also induced to be very rising simultaneously.

NLPCA and PCA may both be useful tools in future analysis of earthquakes and related TEC phenomena. The results of both are not affected by solar activity (e.g. solar flares) in the detection of earthquake-related TEC anomalies as shown in Section 4, and their ability to describe the shape and spatial dimensions of an anomaly might be instructive to a TEC anomaly’s cause.

6. Conclusion

In this study, NLPCA can be used to detect and determine the spatial distribution of a TEC anomaly that occurred at the time of the mainshock of the May 12, 2008 Wenchuan, $M = 7.9$ earthquake of China. Analysis is conducted for the time period 06:00 to 08:00UT on 12 May 2008. In this case results showed that at an altitude of 200 km a wide ranging TEC anomaly is detectable. The range of the anomaly reduces with height but the intensity increases. At a height of 300 km the largest principal eigenvalues are returned. The shape and spatial distribution could be indicative of a very rising acoustic shockwave and snow-plow effects on ionospheric electron plasma.

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References


