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RESEARCH

Karhunen–Loève Transform for Detecting Ionospheric Total Electron Content (TEC) Anomalies Prior to the 1999 Chi-Chi Earthquake, Taiwan

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Abstract—This research uses eigenvalue characteristics of the Karhunen–Loève Transform to investigate GPS network ionospheric total electron content (TEC) anomalies associated with Taiwan's Chi-Chi earthquake of September 21, 1999 (LT) (M_w = 7.6). The transforms are conducted for ionospheric TEC from August 1 to September 20, 1999 (local time), using data from 13 GPS receivers. The data were collected at 22°–26°N Lat. and 120°–122°E Long. Applying the Karhunen–Loève Transform to the GPS receiver data TEC anomalies gave large principal eigenvalues (>0.5 in a normalized set) on August 14 and September 17, 18, and 20, with allowance given for the Dst index, which was quiet for the study period. Comparisons were then made with other researchers who also found TEC anomalies on September 17, 18, and 19 associated with the Chi-Chi earthquake. Consideration is also given to reported ground-level geomagnetic field activity that occurred between mid-August and late October leading up to and including the Chi-Chi and Chia-Yi earthquakes, which are associated with the same series of faults. It is possible that August 14 is representative of an earthquake-associated TEC anomaly. This is an interesting result given how much earlier than the earthquake it occurred.

Keywords: Karhunen–Loève Transform—GPS network ionospheric total electron content (TEC)—Taiwan's Chi-Chi Earthquake

Introduction

In recent years, ionospheric total electron content (TEC) anomalies and their potential association with earthquakes have led some researchers to think that such anomalies could be used in earthquake prediction (Hsiao et al., 2010, Pulinets, 2004, Hayakawa, 2007, Heki et al., 2006, Liperovskaya et al., 2006, Liu et al., 2006, Liu & Gao, 2004, Hegai et al., 2006). This is partly because examination of solid-earth and ionospheric coupling has been greatly improved by GPS satellite coverage whereby TEC anomalies are detectable due to signal delay between ground-based receivers and GPS satellites.

The specific causes of TEC anomalies are not yet known; however, during earthquake preparation, there are many processes that could create TEC depletions and enhancements. The possibilities include: radon ionization producing strong electric fields in the lower atmosphere (Pulinets & Boyarchuk, 2004); local electric fields caused by charge separation in stressed rock whereby positive holes (pholes) flow out of the stressed rock portion to areas of less stress causing charge separation. These pholes can travel long distances from the earthquake-preparation zone deep in the crust to the earth's surface. They concentrate at the ground-to-air interface creating electric field ionization of air molecules (Freund et al., 2009). The turbulence from rapid CO_2 gas release might also create lower-atmosphere electric fields (Voitov & Dobrovolsky 1994). Such lower-atmosphere electric fields could travel along geomagnetic field lines into the ionosphere. A final coseismic aspect that has been closely examined are fine vibrations in the earth's surface creating sub-audible pressure waves that are amplified by density contrast in the atmosphere to produce large amplitude pressure waves which are called "atmospheric gravity waves" in the ionosphere (Garcia et al., 2005).

Other related studies include research into changes in the geomagnetic field in the preparation zone of earthquakes. For example, prior to the M = 7.3 September 21, 1999, Chi-Chi earthquake until after the M = 6.2 October 22, 1999, Chia-Yi earthquake on Taiwan anomalous amplitudes in geomagnetic intensity as high as 200 nTs existed for six weeks leading up to the Chi-Chi earthquake and lasting until after the Chia-Yi earthquake sequence (Yen et al., 2004). The Chi-Chi earthquake occurred due to bedding slip along the Chelungpu fault, and the Chia-Yi earthquake occurred just south of this fault on the Meishan fault, considered the southern boundary of the Chi-Chi earthquake (Yue et al., 2005). Yen et al. (2004) consider the possibility of changes in the geomagnetic field being related to crustal stress during these earthquakes and cite earlier work by Freund (2000) and Bolt (1999) on rapidly moving streaming potentials (mentioned in the above paragraph) and electrical charge transfers due to changes in electrical and hydraulic connectivity patterns by Lorne et al. (1999).

Researching the association between solid-earth and ionospheric TEC anomalies is difficult due to the ionosphere being plasma-like and influenced by many variables requiring reliable earth and sun models. Currently, we do not have enough dependable information to make such models; however, statistical models of real TEC have in the past been able to show association between earthquakes and TEC anomalies. Pulinets et al. (2004) showed that by using the daily cross-correlation coefficient for ionospheric TEC between two ionosondes (one covering the epicenter of the earthquake and the other hundreds of km away) it was possible to identify statistically TEC anomalies occurring up to seven days before mainshock nucleation. Liu and Gao (2004) used a 15-day running median of TEC and the associated interquartile range applied to ground-based GPS-receiver data to measure ionospheric TEC anomalies for 20 ($M \geq 6$) earthquakes (September 1999 to December 2002) on Taiwan. In their study, TEC anomalies occurred in 80% of cases and were prevalent within five days prior to the mainshock. Pulinets et al.'s (2004) use of ionosondes was based on the cross-correlation coefficient for TEC anomalies between two ionosondes being high (~0.9). This is significant because the impact of geomagnetic activity on TEC could be measured simultaneously at both ionosondes, meaning a sharp drop in the correlation would be indicative of a localized TEC anomaly furthering the case for earthquake association. Liu and Gao (2004) established earthquake association for TEC anomalies by using statistical analysis. First, they showed that sparse TEC anomalies occurred on 25% of the days in the study period, giving a 1 in 4 chance of observing a sparse TEC anomaly on any given day. However, their data showed that the chance of an anomaly occurring in the five days before a major earthquake was 44%, which was almost twice the rate for any other 5-day period (23%).

The use of ionosondes to measure TEC is well-established; however, spatial and temporal coverage is limited, making earthquake-related TEC anomaly correlations difficult (Liu & Gao, 2004). Plus TEC maps generated from ionosondes are subject to short-wave fadeout leading to data gaps (Davies, 1990, Liu & Gao, 2004). On the other hand, the number of ground-based GPS receivers is large and growing, giving good coverage, except over oceans.

One inherent weakness of the statistical methods used above is that they rely on a definition of what constitutes normal TEC levels to find anomalies. Defining normal TEC levels is difficult because TEC by nature is not stable in space and time. This means that any theory which relies solely on identifying TEC anomalies as deviations from a statistical average is not immediately apparent even if true. Another issue is that in the case of Pulinets' research the registration of a TEC anomaly depends on the use of ionosondes to determine a localized anomaly through earthquake-associated TEC anomalies that could occur away from the epicenter (Pulinets et al., 2002). Also, ionosonde coverage is not always adequate, and computation of anomalies might require daily records, limiting real-time computation capacity.

To help overcome these issues, in a previous paper (Lin, 2010) I examined the validity of using the Karhunen–Loève Transform (KLT) applied to one-dimensional TEC data gathered near the epicenters of 12 ($M \geq 5.0$) earthquakes that occurred on Taiwan between January 2002 and December 2003. These earthquakes were previously confirmed statistically by Liu et al. (2006) to have earthquake-related anomalies. The results of Lin (2010) confirmed the findings of Liu et al. (2006) that TEC anomalies existed on the days they claimed; however, unlike the "running median" method used in Liu et al. (2006), the KLT method determines the existence of TEC anomalies on the basis of a mathematical index. The KLT method was able to give independent confirmation of Liu et al.'s results. Like the "running median" method applied by Liu et al. (2006) and others, KLT still requires elimination of other potential causes such as solar flare and geomagnetic storm activity. However, Lin (2010) showed that the technique is independent of long-term variance in TEC due to internal ionospheric features. Lin (2010) helped establish criteria for using KLT to discover earthquake-related TEC anomalies. The criteria established allows KLT to detect earthquake-associated TEC anomalies when earthquakes are larger than M ≥ 5.0, detection is within the earthquake preparation zone, and no alternative explanation such as X-ray flux or geomagnetic activity is available to explain the TEC anomalies. This paper gives consideration to the research of Yen et al. (2004), who measured geomagnetic field anomalies between August and October 1999 close to the Chi-Chi and Chia-Yi earthquakes and research by Liu et al. (2001) who found statistically relevant TEC anomalies on September 17, 19, and 20, 1999, pertaining to the Chi-Chi earthquake.

The Karhunen–Loève Transform is applied to local GPS network (Figure 1) ionospheric TEC records from August 1 to September 20 (local time) before the M = 7.6 Chi-Chi earthquake of September 2, 1999 (01:47:159 local time), 23.85°N and 120.78°E at a depth of ~8 km. Data are based on GPS network data collected from 13 GPS receivers (15-min intervals) at 22°–26°N Lat. and 120°–122°E Long. (Figure 1). The results of the transforms are then compared with those of Liu et al. (2001) and the geomagnetic field disturbance that occurred at the earth's surface attributed to the Chi–Chi earthquake by Yen et al. (2004).

The Karhunen–Loève Transform and TEC Data Processing

The Karhunen–Loève Transform

The KLT method is a widely used technique in data analysis. It is a simple non-parametric method that allows the extraction of relevant data from confusing datasets. The technique makes three basic assumptions: linearity, a high signal to noise ratio (SNR), and orthogonal principal components. Linearity allows for the problem to be framed as a change of basis, a high SNR means that principal components with larger variance represent points of interest and those with lower variance represent noise (this assumption is strong and can be incorrect), and orthogonality makes KLT solvable with linear algebra. In general terms, KLT allows for the underlying structure to be seen if the initial assumptions are correct.

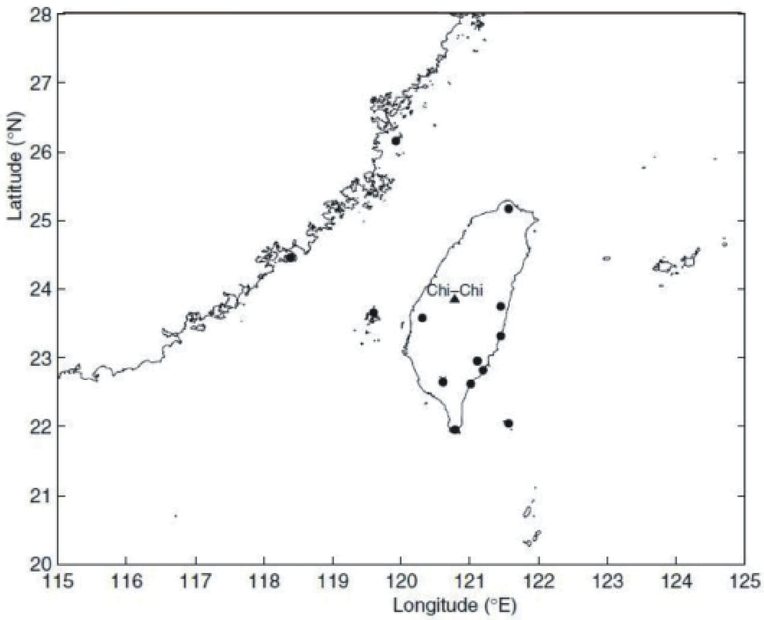


Figure 1. This figure shows the location of 13 GPS receivers (filled circles), and the epicenter of the Chi-Chi earthquake (triangle).

Essentially, the method is a variable reduction method. In the case of TEC anomalies, the TEC data are reduced to see if there are any discernable patterns among the data that could be related to the same construct (earthquake preparation). This is done by reducing the observed variance in TEC to a smaller number of artificial variables called principal components represented by principal eigenvalues. The maximum principal eigenvalue gives the principal characteristics of the signals. An explanation of data and data processing is given in the next section. The transform matrix is given in Equation (1) below. The input TEC Signals X form a matrix A with m rows and n columns:

$$A = [X]_{m \times n} \tag{1}$$

For each n, u is a unit vector. If we let $AA^T u = \lambda u$, then the eigenvalues are $\lambda_1 \geq \lambda_2 \geq .... \geq \lambda_m$ (output data). The maximum eigenvalue (principal eigenvalue) λ_1 represents the principal characteristics of signals.

TEC Record Processing Using Karhunen–Loève Transform

The Karhunen–Loève Transform is applied to data from August 1 to September 20, 1999. The daily data were collected from 13 GPS receivers (15-min intervals) at 22°–26°N Lat. and 120°–122°E Long. (Figure 1). The 15-minute intervals mentioned suggest that the GPS data were obtained from certain GPS satellites that appear over the horizon every 15 minutes. The Chi-Chi earthquake (M_w = 7.6) occurred at 01:47:159 (LT) on September 21, 1999, at 23.85°N and 120.78°E at a depth of ~8 km. For TEC characteristics to be described on a day-to-day basis, the TEC records for a day form matrices of dimensions 13 rows (receivers) (m) and 96 columns (a day) (n), and these are used as inputs to Equation (1) to output a principal eigenvalue for this day.

The principal eigenvalues generated are representative of daily TEC. Figure 2 shows the principal eigenvalues from August 1 to September 20 for the TEC records that are mentioned above. All of the principal eigenvalues are normalized by dividing by the maximal value. Principal eigenvalues are considered large when they are >0.5 in a normalized set (Lin, 2010). The magnitudes of principal eigenvalues are large on August 14 and September 17, 18, and 20.

Results and Discussion

Figure 2 gives the results of the KLT conducted for August 1 to September 20, 1999. Four large principal eigenvalues are found for the time period August 14, and September 17, 18, and 20. Figure 3a–d shows the latitude–time–TEC plots obtained from the Taiwan GPS network (Liu et al., 2001) on August 14 and September 17, 18, 20, before the Chi-Chi earthquake. Figure 3e is a normal day. Note depletions are evident at the approximate latitude of the Chi-Chi earthquake according to Figure 3a–d. The results for September 17, 18, and 20 are similar to those of Liu et al. (2001) who also found TEC anomalies for these dates. In that study, Liu et al. combined data from 13 GPS receiver stations with time and spatial variations in TEC prior to the Chi-Chi earthquake and found statistically significant decreases in TEC one, three, and four days before the earthquake based on a 15-day running median for TEC. Taiwan lies under the northern boundary of the equatorial ionospheric anomaly (EIA), and Liu et al.'s paper describes an equatorialward shift of the EIA for the afternoon periods of September 17, 18, and 20. Similarly, Tsai et al. (2006) utilizing a 15-day median and the assumption of a normal distribution found with an 80 to 85% confidence level TEC anomalies on September 17 and 18 for the time period 10:00 to 20:00 (LT). In a later study, Nishihashi et al. (2009) examining the spatial extent of GPS–TEC related TEC anomalies found that it was possible the September 17 anomaly could have been influenced by geomagnetic storm activity; however,

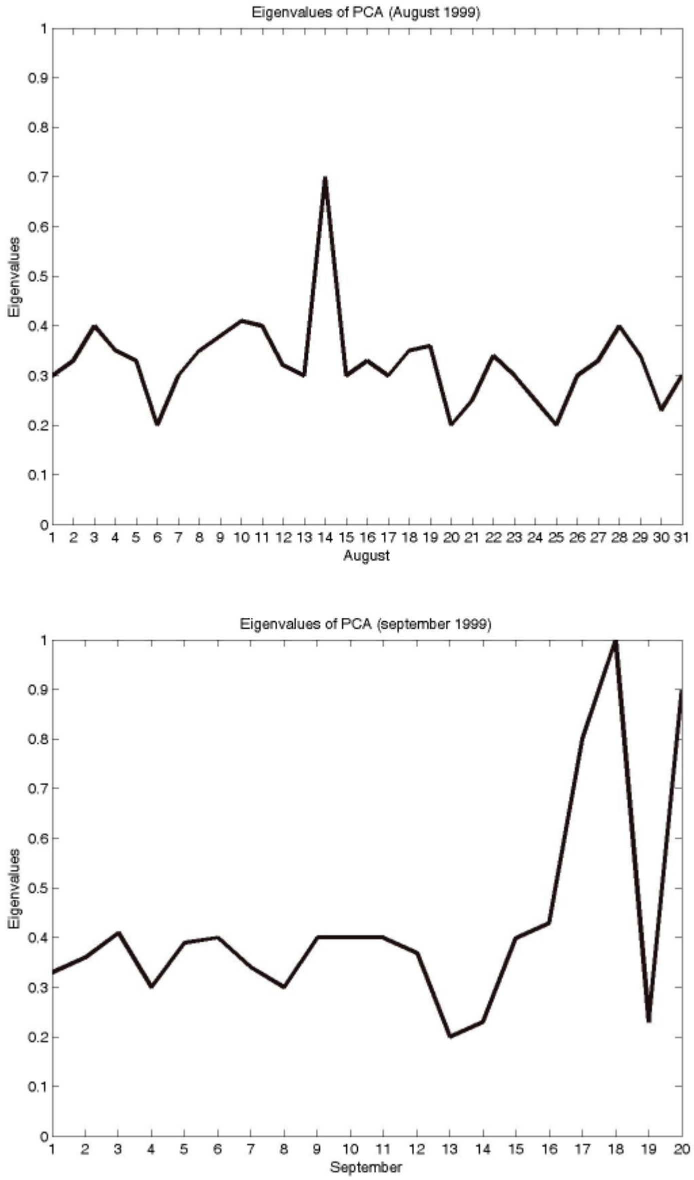
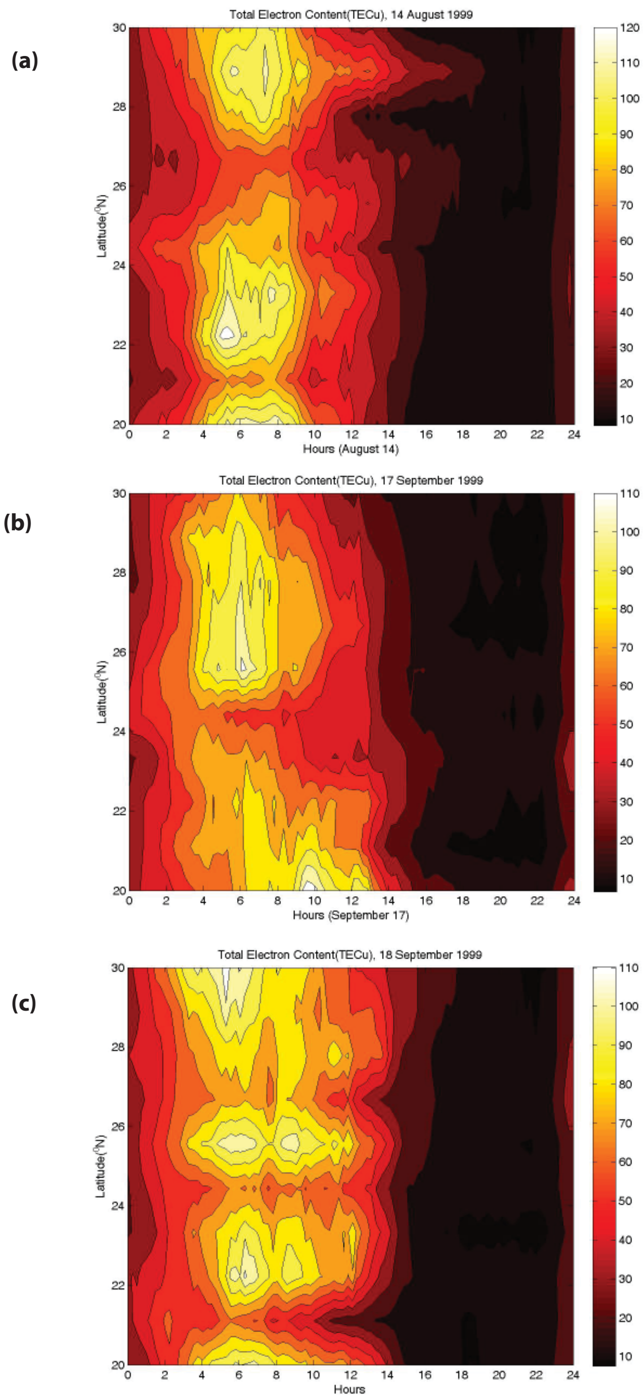
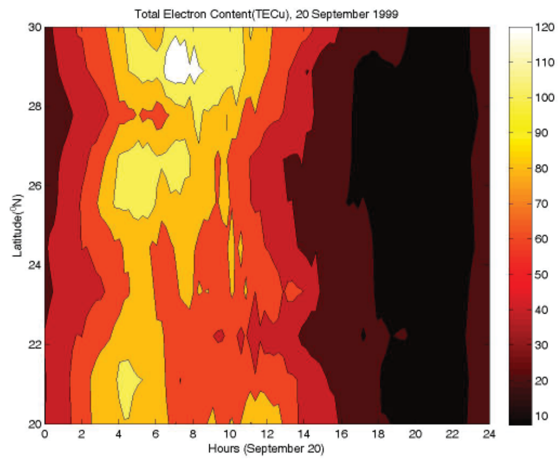


Figure 2. This figure shows eigenvalues assigned to ionospheric TEC from August 1 to September 20, 1999. Dates constitute the horizontal axis, and corresponding eigenvalues are on the vertical axis. Peaks and troughs in eigenvalues have been plotted and graphed on a day-to-day basis to allow for interpolation.


(a)
Total Electron Content(TECu), 14 August 1999
Latitude(°N)
Hours (August 14)
(b)
Total Electron Content(TECu), 17 September 1999
Latitude(°N)
Hours (September 17)
(c)
Total Electron Content(TECu), 18 September 1999
Latitude(°N)
Hours

(d)



(e)

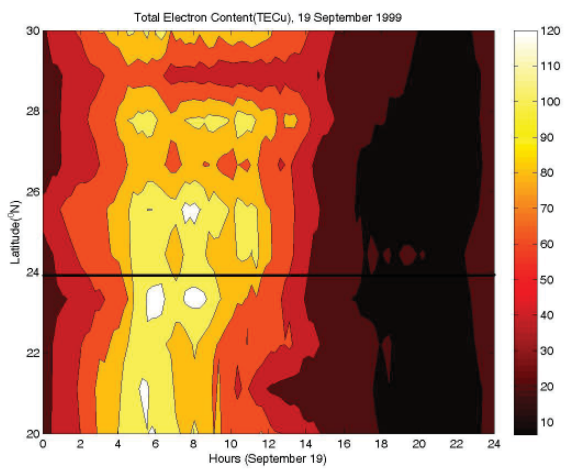


Figure 3. The latitude–time–TEC plots obtained from the Taiwan GPS network on August 14, and September 17, 18, 20, before the Chi-Chi earthquake. (e) is a normal day. The line shows the latitude of the Chi-Chi earthquake.
(a) August 14, 1999.
(b) September 17, 1999.
(c) September 18, 1999.
(d) September 20, 1999.
(e) September 19, 1999.

the study confirmed September 18 and 20 as potentially earthquake-related TEC anomaly days.

As mentioned in the Introduction, Yen et al. (2004) measured geomagnetic activity associated with the 1999 Chi-Chi and Chia-Yi earthquakes. These two earthquakes are closely related to a series of faults that include the Chelungpu, Tachiashan, Meishan, Luliao, and Chushiang faults, all of which are thought to have been active during the Chi-Chi and Chia-Yi earthquake sequence. Geomagnetic fluctuations for southern Taiwan were measured by a series of 7 magnetometers distributed across seismic zones throughout southern and eastern Taiwan with an additional reference station in seismically quiet northern Taiwan. The study conducted from mid-August to November 1999 found frequent fluctuations in geomagnetic intensity caused by earthquake preparation processes for six weeks leading up to the Chi-Chi earthquake until right after the October 22 Chia-Yi earthquake, after which time geomagnetic activity became quiet very abruptly (figure 2 in Yen et al. 2004). The causes of geomagnetic fluctuations are not completely understood.

Yen et al. (2004) consider the possibility of intense electric fields created by charge separation developing in stressed rocks when pholes move away from the stressed rock areas (Freund, 2000) as described in the Introduction and also streaming potentials caused by changes in the hydraulics of crustal rocks and sediments (Lorne et al., 1999). Considering these results in association with those given in Figure 2 for the KLT, a large principal eigenvalue was found on August 14 and for the days close to the Chi-Chi earthquake. August 14 is earlier than the collection date for geomagnetic activity given by Yen et al. (2004). While their paper and a consequent paper by Tsai et al. (2006) do not mention why mid-August was chosen as the commencement date for observing geomagnetic activity associated with these two earthquakes, one can assume this is probably because that is when they first noted anomalous activity. This would mean the August 14 anomaly perhaps occurred when earthquake-related geomagnetic activity was in a quiet period. However, that would need to be confirmed.

The August 14 result, however, is interesting in another way. It occurred well before the Chi-Chi earthquake on a geomagnetic quiet day according to the Dst. Index (Figure 4). The result is similar for that of September 17, 18, and 20 (also quiet days by the Dst Index), where KLT confirmed the results of TEC anomalies associated with the Chi-Chi earthquake by Liu et al. (2001), Tsai et al. (2006), and Nishihashi et al. (2009). It is possible that the TEC anomaly of Aug. 14 is earthquake-related, and it occurred well before the dates discovered above by these other researchers, all of whom used 15-day running medians before the Chi-Chi earthquake. The reason this is done is because past research by Chen et al. (2004) showed that the observation of earthquake-associated

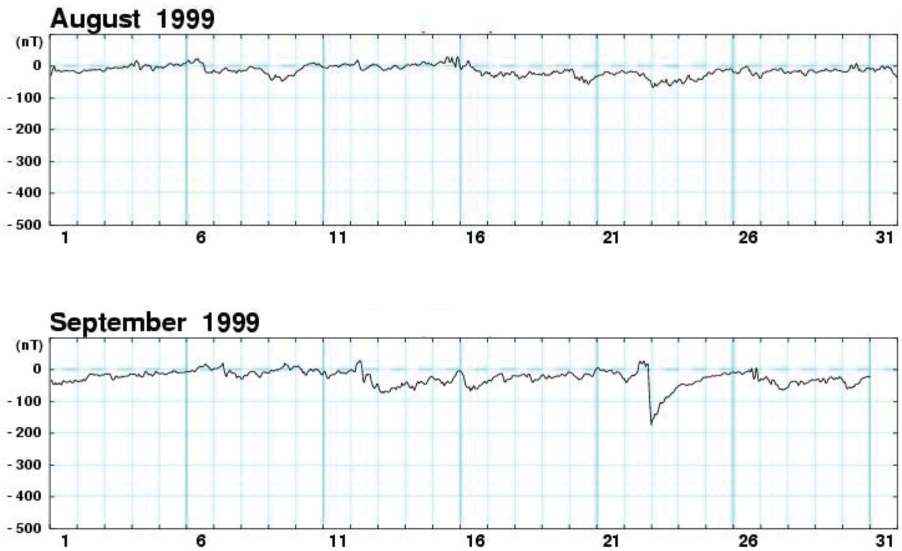


Figure 4. Dst index from August 1, 1999 to September 30, 1999.

TEC anomalies in Taiwan for M ≥ 5 earthquakes in the 1 to 5 days before an earthquake (1994 to 1999) was not due to statistical chance. This they proved with a simple coin-toss comparative study. However, if KLT has the ability to determine earthquake-associated anomalies based on a firmer mathematical footing than statistical association (deviations from a running median), then August 14 could possibly be an earthquake-associated anomaly.

Two recent studies of the China, May, 12, 2008, Wenchuan earthquake (Kakinami et al., 2010, Jhuang et al., 2010) using empirical studies with normalized TEC data found possible earthquake-related TEC anomalies on days 6 and 13 before that earthquake. Their results are important in that they help support the result given in this work.

Conclusion

The Karhunen–Loève Transform (KLT) is applied to data from 13 GPS receivers to detect earthquake-associated TEC anomalies related to Taiwan's Chi-Chi earthquake of September 21, 1999 (LT) (M_w = 7.6). The transforms are conducted for ionospheric TEC from August 1 to September 30, 1999 (local time). Data collection was for the region 22°–26°N Lat. and 120°–122°E Long. TEC anomalies were given by large principal eigenvalues (>0.5 in a normalized set) for September 17, 18, and 20, and August 14 with consideration given for the Dst. Index, which was quiet for the study period. Comparisons are made with the work of other researchers such as Liu et al. (2001) who also identified TEC anomalies for these days through deviations from a 15-day running median and Yen et al. (2004) who reported intense geomagnetic field activity at a ground level leading up to the Chi-Chi earthquake until after the October 22, 1999, Chia-Yi earthquake. Both these earthquakes are associated with the same series of faults. The comparative results for KLT with ground-level geomagnetic activity are inconclusive. The possibility, however, exists that August 14 had an earthquake-associated TEC anomaly earlier than the 1-to-5–day period currently used to find these anomalies.

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