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Ionospheric Total Electron Content (TEC) Anomalies Associated with Earthquakes through Karhunen-Loéve Transform (KLT)

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ABSTRACT

This research uses eigenvalue characteristics of the Karhunen-Loéve Transform of ionospheric total electron content (TEC) to investigate precursors for 12 earthquakes of Richter magnitude scale M 5.0 in a local region of latitude 23.00 to 24.00 N and longitude 120.00 to 121.50 E for 1 January 2002 to 31 December 2003. Previous researchers have found that in the 5 days before these earthquakes (i.e., prior to M 5.0), precursors of clear ionospheric anomalies showing sparser total electron content (TEC) were detected through statistical investigation. This was evidenced through two issues from Liu and his partners in 2001 and 2006. These issues gave credible evidence of such precursors. The precursor days having clear extreme eigenvalues of the Karhunen-Loéve Transform as the precursors instead of the sparser ionospheric TEC were also mostly in the 5 days before the 12 earthquakes of greater than M 5.0. The precursors of Chi-Chi Earthquake ($M_w = 7.6$) with clear extreme eigenvalues were detected on the 1st, 3rd, and 4th days before this earthquake. These results are consistent with the analyses of Liu and his partner's issue in 2001. These findings verify the validity of the Karhunen-Loéve Transform. To further verify this approach, the Karhunen-Loéve Transform is applied to an earthquake in Japan. Precursors to the Japan Iwate-Miyagi Nairiku earthquake ($M_j = 7.2$), with clear extreme eigenvalues are detected on the 1st, 2nd, and 5th days before the earthquake, respectively. However, after detailed analysis, precursors of earthquakes of Richter magnitude scale M < 5 are not easy to identify using extreme eigenvalues because of existence of other ionospheric features not caused by earthquakes.

Key words: Precursors, Karhunen-Loéve transform, Ionospheric total electron content (TEC), Taiwan Chi-Chi earthquake, Japan Iwate-Miyagi Nairiku earthquake

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1. INTRODUCTION

Typical traditional analyses of precursors to earthquakes look at a variety of phenomena such as energy release with electric and magnetic field disturbances and hot spring analyses (Kuo et al. 2006). However, such precursors are not easily recorded and are subject to intrusion by radio waves. In more recent years, there has been a focus on the detection of ionospheric anomalies in precursor research (Liu et al. 2001, 2006; Pulinets 2004; Hegai et al. 2006; Heki et al. 2006; Liperovskaya et al. 2006; Hayakawa 2007). This body of research has confirmed some ionospheric anomalies having relationships with earthquakes, but such relationships have not been suitably mathematically described; they have relied on observational analyses, which can be subjective. For example, some researchers have found that mostly in the 5 days prior to large earthquakes (i.e., prior to M 5.0), clear ionospheric anomalies exhibiting sparse total electron content (TEC) were detected via statistical analysis (Liu et al. 2006). This credible research is of great importance in detecting precursors to large earthquakes; however, research based on observations can be criticized for being subjective. To improve the acceptability of such research, there is a need to define what constitutes normal TEC to prove an anomaly of sparse ionospheric TEC. Moreover, it can be argued that it is meaningless to define a normal ionosphere for TEC given that the ionosphere functions as a type of plasma, which by nature is unstable because electron density is not a constant fixed in position and time. Therefore a theory pertaining to sparser ionospheric TEC as an anomaly is not immediately acceptable for identifying pre-

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cursors to earthquakes. In this study, precursors of earthquakes will be detected using eigenvalue characteristics of the Karhunen-Loéve Transform for two-year ionospheric TEC records. This method is advantageous in that it is not necessary to define normal ionospheric TEC. Previous mathematical modeling of seismo-ionospheric coupling does exist (Pulinets et al. 2002, 2004, 2007). These issues examine how local changes in the earth's crust affected parameters governing the electrical relationship between the ground and the ionosphere, specifically changes in ionospheric electron content. Pulinets et al.'s research shows that the registration of an ionospheric electron content precursor anomaly is dependent on the focus of the earthquake (Pulinets et al. 2002). It also requires TEC records at different positions (Pulinets et al. 2004) and might sometimes require the entire TEC record of a single day, meaning the precursor could not be registered in real time (Pulinets et al. 2007).

The Karhunen-Loéve Transform has been widely used to detect and recognize fine characteristics of signals; its physical meaning is indubitable and known (Lu and Dang 2007; Ringberg et al. 2007; Ying et al. 2007) making it highly suitable for examining ionospheric anomalies and their association with earthquakes. Further, studies by Hattori's and Serita (Hattori et al. 2004, 2006; Serita et al. 2005) achieved excellent results applying this transform to ULF geomagnetic data observed at several closely separated stations. In this study, we apply the Karhunen-Loéve Transform to two years of ionospheric TEC records to detect anomalies earthquake related TEC anomalies given by clear extreme (here maximal) eigenvalues and cross reference the result of this work with that of Liu's analysis (Liu et al. 2001, 2006) to verify the credibility of the Karhunen-Loéve Transform. The primary advantage of the Karhunen-Loéve Transform method is its innate objectivity; however, it has two other advantages in that signals can be computed at speeds approaching real time when the selected gain is small enough (see section two such that the dimensions of signals can be reduced in the computing process to improve computing time. In addition, as will be seen later, results of the Karhunen-Loéve Transform are not affected by the focus of an earthquake. These additional advantages overcome two of the difficulties raised in Pulinets et al.'s aforementioned research. Thus the Karhunen-Loéve Transform provides both the objectivity of a mathematical approach and the practicality of fast real-time computation of ionospheric TEC anomalies for earthquake precursor analysis.

2. THEORY OF KARHUNEN-LOÉVE TRANSFORM

In this section, the theory of Karhunen-Loéve Transform (Londoño et al. 2005; Montagne and Vasconcelos 2006) is explained. The signals form a matrix A with m rows and n columns (n is also called the selected gain):

$$A = \begin{bmatrix} x_{1 \times 1} \cdots\cdots\cdots x_{1 \times n} \\ \downarrow \\ x_{m \times 1} \cdots\cdots\cdots x_{m \times n} \end{bmatrix} \tag{1}$$

If $\sum_{i=1}^{m} x_{m\ n} \quad 0$, then each n, and $p = A^T u$ is the projection on a unit vector u. When $J(u) = p^T p = u^T AA^T u$, and then $\tilde{J}(u) = u^T AA^T u + \lambda(1 - u^T u)$ is injected as a Lagrange Multiplier. Let $_u\tilde{J} \quad 0 \quad AA^T u = \lambda u$, then the eigenvalues of $J(u)$ are $\lambda_1 \quad \lambda_2 \quad \ldots\ldots \quad \lambda_m$ and the corresponding eigenvectors are u_1, u_2 to u_m. The maximum eigenvalue (principal eigenvalue) is λ_1 on the eigenvector $u = u_1$, which represents the principal characteristics of signals. The corresponding projection p_1 is the principal energy of signals. Therefore, the Karhunen-Loéve Transform is also called principal component analysis (PCA). Later in this study, the term "PCA" is used instead of the Karhunen-Loéve Transform.

3. TEC RECORD PROCESSING USING PRINCIPAL COMPONENT ANALYSIS (PCA)

The eigenvalue characteristics of the PCA for one-dimensional ionospheric total electron content (TEC) records (data pre 15 minutes), which are triggered by GPS satellites and received by hundreds of ground network stations of the Central Weather Bureau (CWB) of Taiwan, from 1 January 2002 to 31 December 2003 (local time) are used to detect precursors of earthquakes in a localized region of latitude 23.00 to 24.00 N and longitude 120.00 to 121.50 E. In order to perform PCA, these two-year TEC records are divided into 730 records, and then each of them has the dimension of $m = 1$ row and $n = 96$ columns for a day in order to perform the day-to-day basis analysis. Thus inputting data of a day into the matrix of Eq. (1), an eigenvalue is computed, which represents principal characteristic of TEC signals for a day. In such a manner, an eigenvalue can represent ionospheric TEC characteristic for a day so that such TEC characteristics can be described on a day-to-day basis in order to make comparisons with Liu's credible analysis (Liu et al. 2001, 2006). Information regarding 12 earthquakes of Richter magnitude scale M 5.0 occurring in this time interval and region are listed in Table 1. The figures from Figs. 1 to 7 show their corresponding ionospheric TEC records and the eigenvalues of the PCA. All of the eigenvalues from Figs. 1 to 12 are divided by the maximal eigenvalue in Fig. 5 (same data source allows for this maximal eigenvalue to be 1). Thus the magnitudes for all of the eigenvalues are less than 1.

4. DISCUSSION

By analyzing the 12 earthquakes (M 5.0) listed in

Table 1, except for earthquakes on 9 and 14 November 2003, precursors can be represented using clear extreme eigenvalues instead of sparse ionospheric TEC. These results match Liu's credible analysis (Liu et al. 2006) of sparse ionospheric TEC anomalies prior to large earthquakes. Precursors of clear extreme eigenvalues values for ionospheric TEC existed mostly in the 5 days before the earthquakes shown in Table 1. The PCA used to determine these precursors gives a mathematical representation of earthquake precursors by using clear extreme eigenvalues instead of observations of sparse ionospheric TEC, which can be subjective and require a value to be assigned for a normal level of TEC in the ionosphere - something that is difficult to quantify. The PCA has shown itself to be both credible and advantageous. In Fig. 7, three clear extreme eigenvalues exist on 2, 4, and 10 November, but four earthquakes of Richter magnitude 5.0 occurred in this month. Precursors for the earthquakes on 9 and 14 November are not evident using the PCA. The reason for this could be the time interval between these earthquakes being too short. This would mean that clear extreme eigenvalues could not be estimated for ionospheric TEC. The curves of eigenvalues for Figs. 1 to 7 are

Table 1. This table lists information on 12 earthquakes of Richter magnitude scale $M \geq 5.0$ that occurred in a localized region of latitude 23.00 to 24.00°N and longitude 120.00 to 121.50°E from 1 January 2002 to 31 December 2003 and precursors of these earthquakes with clear extreme eigenvalues of the PCA to corresponding ionospheric TEC records.

	Date (d/m/y)	**Time (local)**	**Magnitude**	**Ionospheric TEC precursors**
1	21 October 2002	18:49:42.3	5.2	on 4th day before the earthquake
2	28 October 2002	18:24:34.2	5.5	on 5th day before the earthquake
3	10 November 2002	08:07:03.7	5.7	on 1st day before the earthquake
4	07 December 2002	11:45:08.7	5.1	on 1st day before the earthquake
5	23 December 2002	19:54:17.5	5.0	on 5th day before the earthquake
6	17 January 2003	21:23:29.4	5.0	on 4th day before the earthquake
7	03 April 2003	14:59:33.7	5.0	on 1st day before the earthquake
8	30 October 2003	17:13:14.7	5.4	on 1st day before the earthquake
9	06 November 2003	21:58:38.8	5.2	on 2nd and 4th days before the earthquake
10	09 November 2003	13:35:49.8	5.4	Not found
11	12 November 2003	08:02:36.0	5.5	on 2nd day before the earthquake
12	14 November 2003	23:54:04.2	5.1	Not found

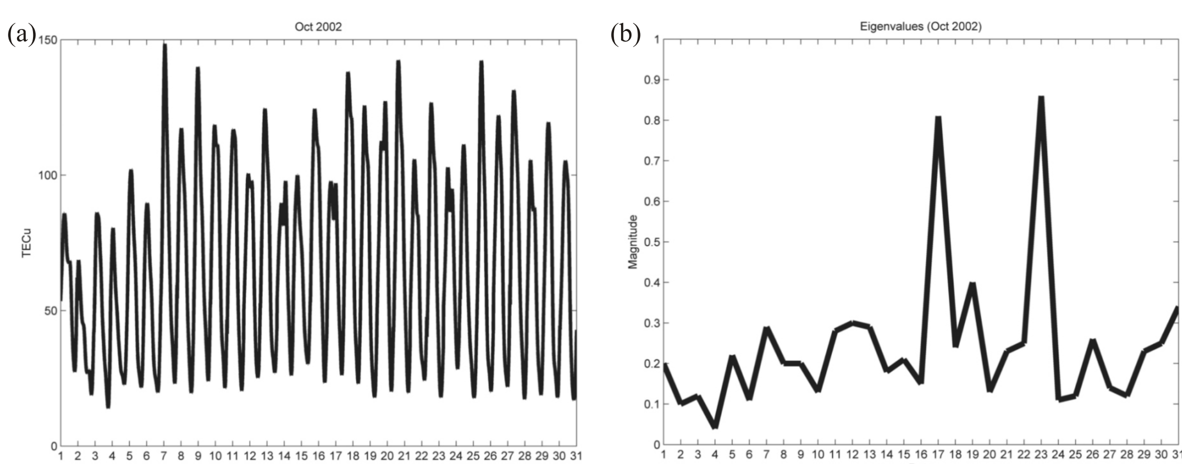

Fig. 1. (a) The figure shows the ionospheric TEC record from 1 to 31 October 2002. The earthquakes occurred on 21 and 28 October. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. Dates constitute the horizontal axis and corresponding eigenvalues are on the vertical axis. Peaks and troughs in eigenvalues have been plotted and graphed on a day-to-day basis to allow for interpolation. Figures 2 to 15 follow the same scheme. Clear extreme eigenvalues instead of sparser ionospheric TEC are apparent on 17 and 23 October (two arrows).

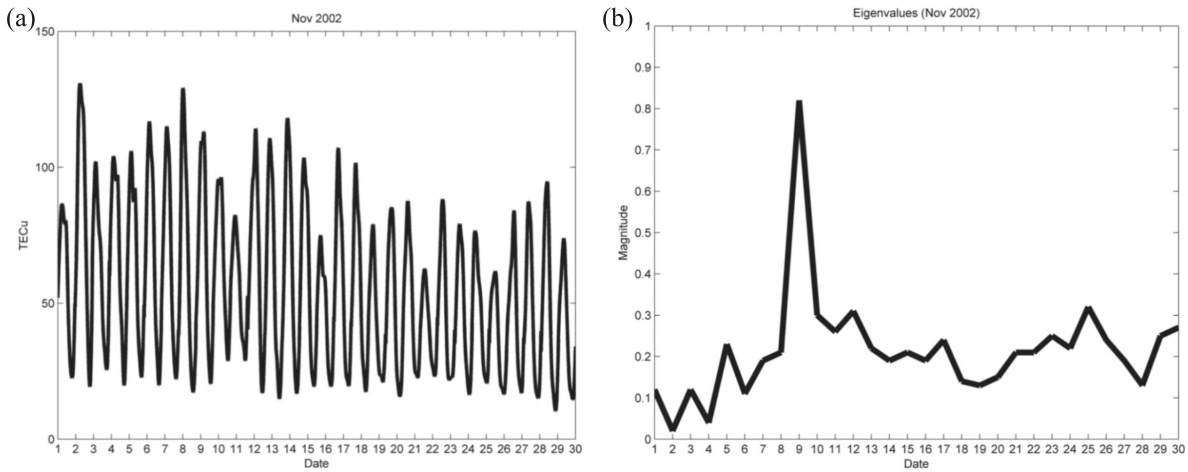

Fig. 2. (a) The figure shows the ionospheric TEC record from 1 to 30 November 2002. The earthquake occurred on 10 November. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. A clear extreme eigenvalue instead of sparser ionospheric TEC on 9 November is indicated by the arrow.

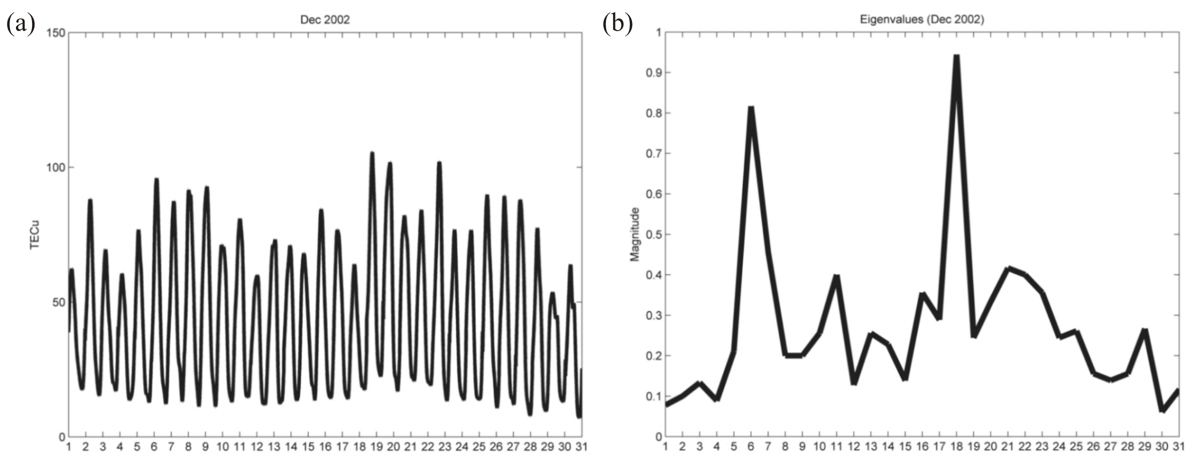

Fig. 3. (a) The figure shows the ionospheric TEC record from 1 to 31 December 2002. The earthquakes occurred on 7 and 23 December. (b) The figure shows eigenvalues using the PCA to this ionospheric TEC record. Two clear extreme eigenvalues instead of sparser ionospheric TEC are apparent on 6 and 18 December (two arrows).

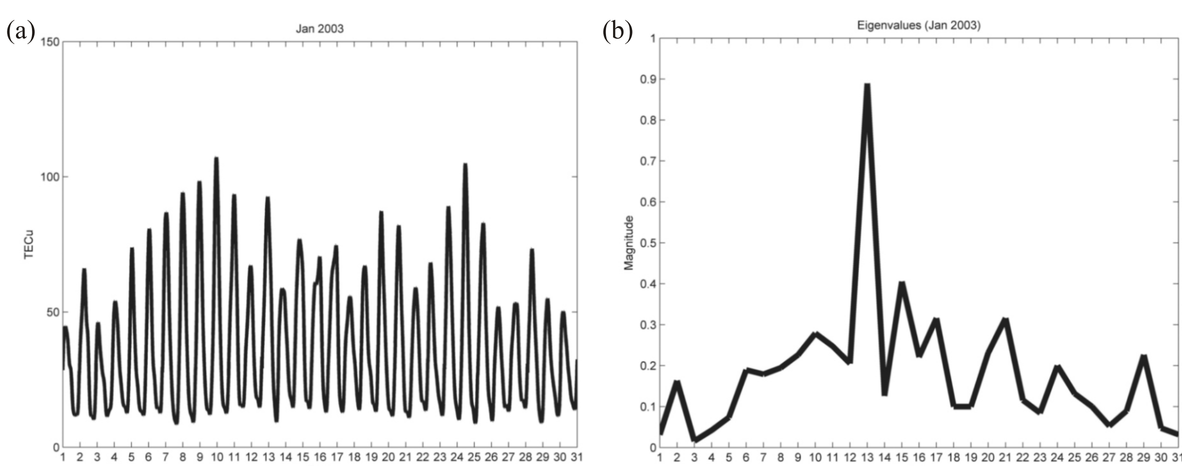

Fig. 4. (a) The figure shows the ionospheric TEC record from 1 to 31 January 2003. The earthquake occurred on 17 January. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. A clear extreme eigenvalue instead of sparser ionospheric TEC on 13 January is indicated by the arrow.

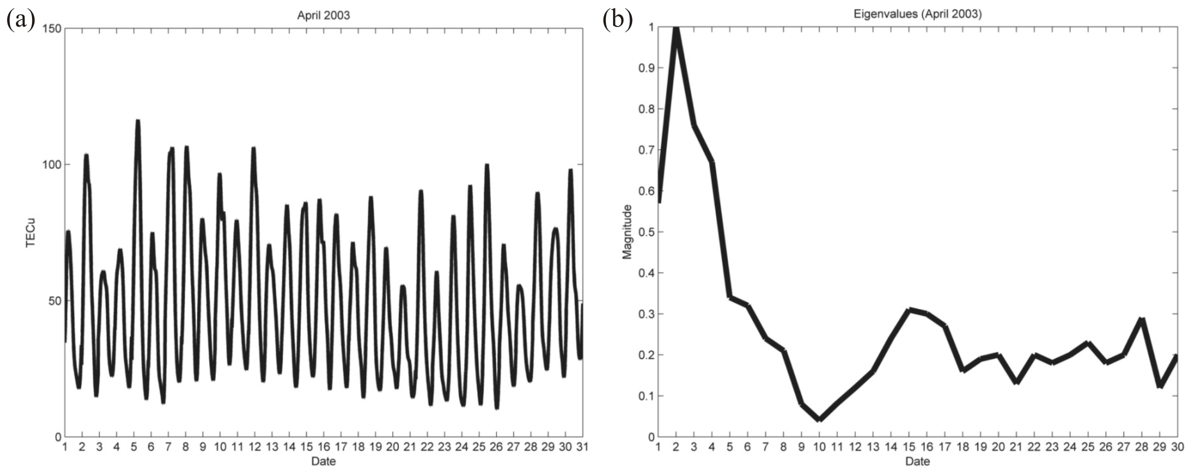

Fig. 5. (a) The figure shows the ionospheric TEC record from 1 to 30 April 2003. The earthquake occurred on 3 April. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. A clear extreme eigenvalue instead of sparser ionospheric TEC on 2 April is indicated by the arrow.

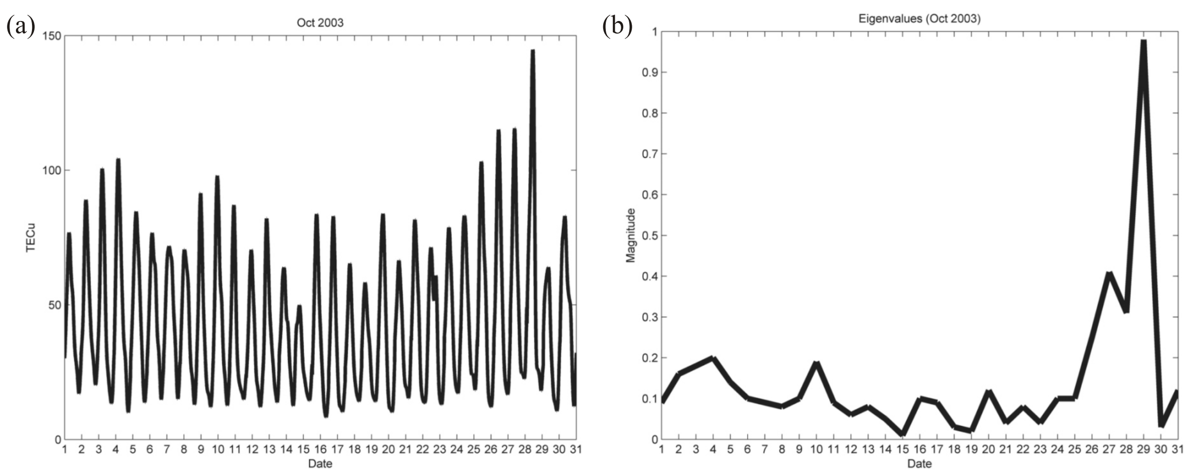

Fig. 6. (a) The figure shows the ionospheric TEC record from 1 to 30 October 2003. The earthquake occurred on 30 October. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. A clear extreme eigenvalue instead of sparser ionospheric TEC on 29 October is indicated by the arrow. Note the magnitude of eigenvalue on 29 October is less than one.

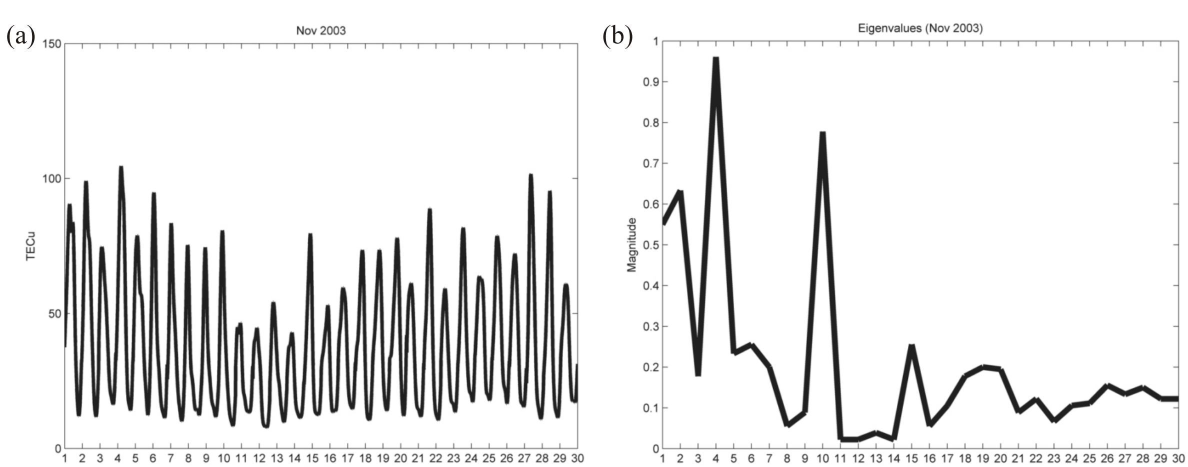

Fig.7. (a) The figure shows the ionospheric TEC record from 1 to 30 November 2003. The earthquakes occurred on 6, 9, 12, and 14 November. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. Three extreme eigenvalues instead of sparser ionospheric TEC are apparent on 2, 4, and 10 November (three arrows). Note the magnitude of the eigenvalue on 4 November is less than one.

not flat and they indicate extreme eigenvalues but of smaller magnitude. Note the term small magnitude extreme eigenvalues is a relative comparison between the extreme eigenvalues otherwise seen in the figures and the magnitudes of clear extreme eigenvalues. The reason for small extreme eigenvalues could be other earthquakes of small magnitude or other ionospheric anomalous disturbances. For example, in Fig. 4, a small extreme eigenvalue on 24 January 2003 may be the precursor for the earthquake (M = 4.5) on 27 January 2003 shown in Table 2, but this is not certain; the explanation for which will be given later.

Figures 8 to 12 show ionospheric TEC records and their corresponding eigenvalues of the PCA for the 52 earthquakes of Richter magnitude scale 3.0 < M < 5.0 that occurred in the study region (Table 2). These earthquakes and their potential corresponding extreme eigenvalues from the PCA are examined to determine whether the PCA is useful in determining precursors for smaller earthquakes. In Fig. 8, a possible small extreme eigenvalue is given for the date 8 February 2003 and an earthquake of M = 4 did occur on 11 February 2003. Similarly, in Fig. 9 a possible small extreme eigenvalue is reported for 13 May 2003 and an earthquake (M = 4.0) occurred a few days later on 15 May 2003. In June 2003, however, there were no earthquakes reported yet a small extreme eigenvalue is given on 15 June (Fig. 10). The value of this eigenvalue is little different from those two extreme eigenvalues of Figs. 8 and 9. A similar comparison can be made between the small extreme eigenvalue of 5 July 2003

Table 2. This table lists information regarding 52 earthquakes of Richter magnitude scale 3.0 < M < 5.0 that occurred in the same region as Table 1.

	Date (d/m/y)	Time (local)	Magnitude		Date (d/m/y)	Time (local)	Magnitude
1	1 October 2002	07:50:14.2	4.1	27	27 February 2003	05:02:35.4	3.0
2	7 October 2002	08:55:48.4	4.3	28	11 May 2003	04:14:25.3	3.7
3	11 October 2002	23:49:59.1	3.6	29	15 May 2003	17:16:30.9	4.0
4	15 October 2002	13:40:6.4	3.9	30	29 May 2003	08:57:49.8	4.0
5	16 October 2002	08:45:41.7	3.6	31	1 April 2003	19:39:58.9	4.4
6	24 October 2002	21:52:31.2	3.7	32	10 April 2003	12:39:46.3	3.8
7	8 November 2002	11:41:42.6	3.8	33	10 April 2003	12:44:24.9	3.9
8	22 November 2002	21:27:34.6	4.1	34	11 April 2003	21:53:20.3	3.9
9	26 November 2002	13:40:12.0	4.2	35	12 April 2003	15:47:40.5	3.7
10	1 December 2002	07:28:55.9	3.3	36	27 April 2003	02:37:35.7	3.6
11	2 December 2002	22:45:11.8	3.2	37	9 July 2003	15:32:54.1	4.4
12	10 December 2002	16:29:10.0	4.3	38	13 July 2003	03:17:34.7	4.4
13	23 December 2002	05:11:38.8	3.5	39	13 July 2003	14:43:55.1	3.5
14	23 December 2002	09:06:39.7	3.1	40	14 July 2993	09:14:5.3	3.9
15	1 January 2003	00:36:48.3	4.1	41	28 July 2003	08:13:3.9	3.7
16	20 January 2003	03:46:2.2	4.1	42	29 July 2003	23:43:13.2	4.1
17	27 January 2003	02:59:22.3	4.5	43	31 July 2003	09:37:9.2	3.8
18	30 January 2003	14:20:25.8	3.8	44	3 October 2003	23:28:10.2	3.9
19	2 February 2003	04:00:5.6	3.8	45	6 October 2003	10:31:30.4	3.5
20	2 February 2003	08:41:59.7	3.7	46	7 October 2003	18:01:3.0	3.5
21	6 February 2003	23:56:49.7	3.9	47	18 October 2003	12:44:27.1	3.9
22	11 February 2003	11:05:17.5	4.1	48	22 October 2003	07:23:19.8	3.8
23	16 February 2003	07:36:11.2	3.8	49	27 October 2003	01:54:29.2	3.8
24	16 February 2003	07:36:49.6	3.5	50	29 October 2003	06:56:10.7	3.3
25	22 February 2003	03:20:58.4	3.2	51	7 November 2003	16:41:58.3	4.3
26	22 February 2003	23:17:40.0	3.9	52	15 November 2003	02:11:21.2	4.4

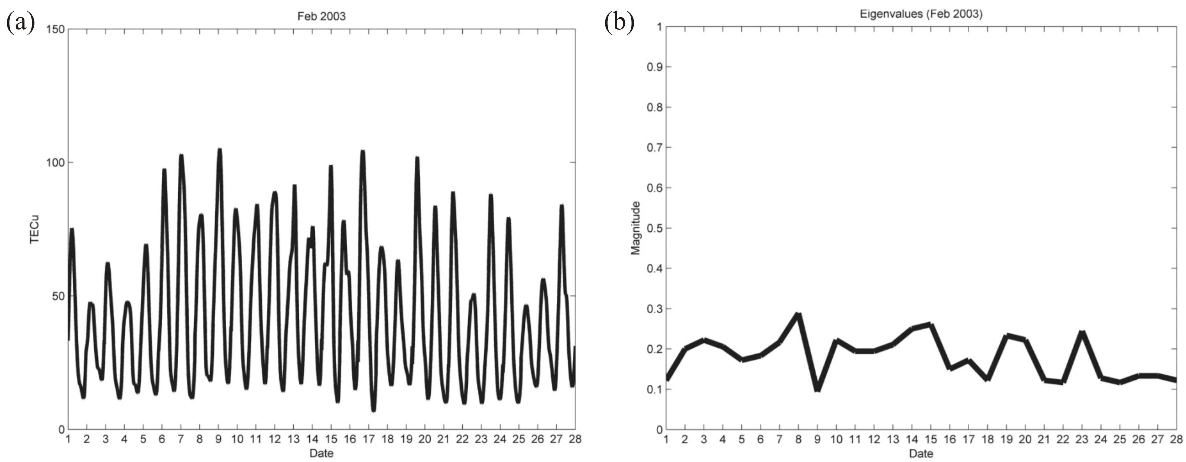

Fig.8. (a) The figure shows the ionospheric TEC record from 1 to 28 February 2003. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. The largest Richter magnitude scale earthquake (M = 4.1) to occur in this month for the research region was on 11 February.

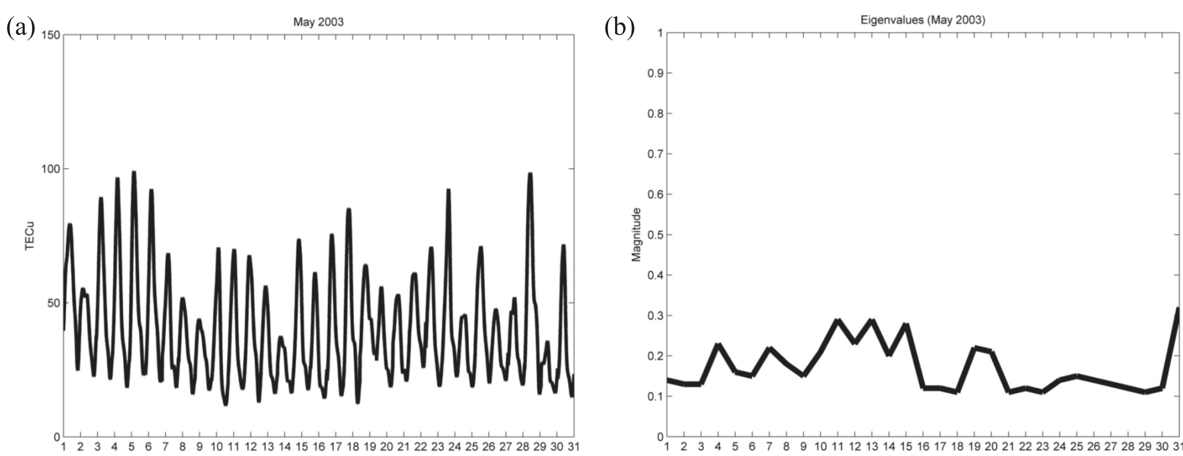

Fig. 9. (a) The figure shows the ionospheric TEC record from 1 to 31 May 2003. (b) The figure shows eigenvalues using the PCA to this ionospheric TEC record. The largest two earthquakes to occur in the research region for this month were of Richter magnitude scale M = 4.0 on 15 and 29 May.

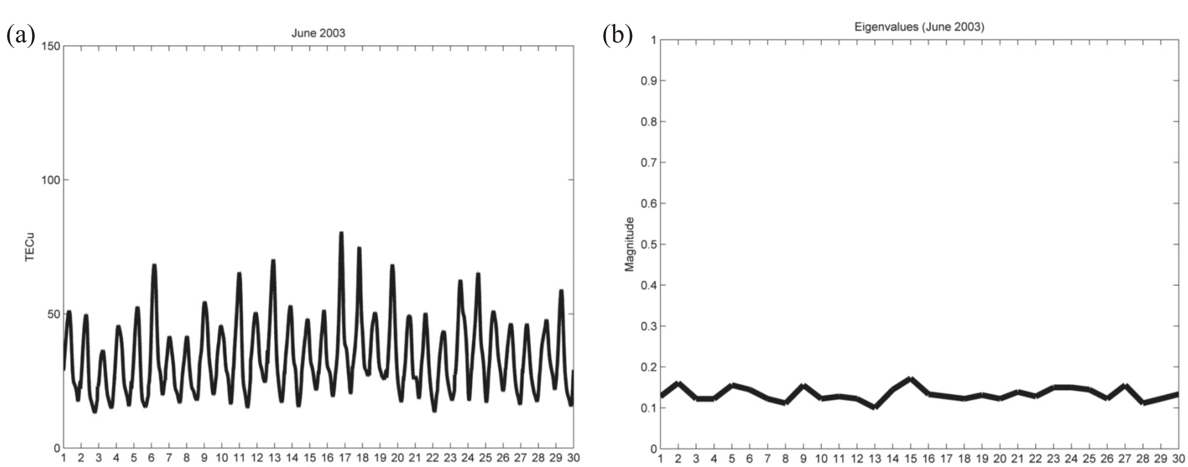

Fig.10. (a) The figure shows the ionospheric TEC record from 1 to 30 June 2003. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. Note the small extreme eigenvalues; no earthquakes occurred in the research region for this month.

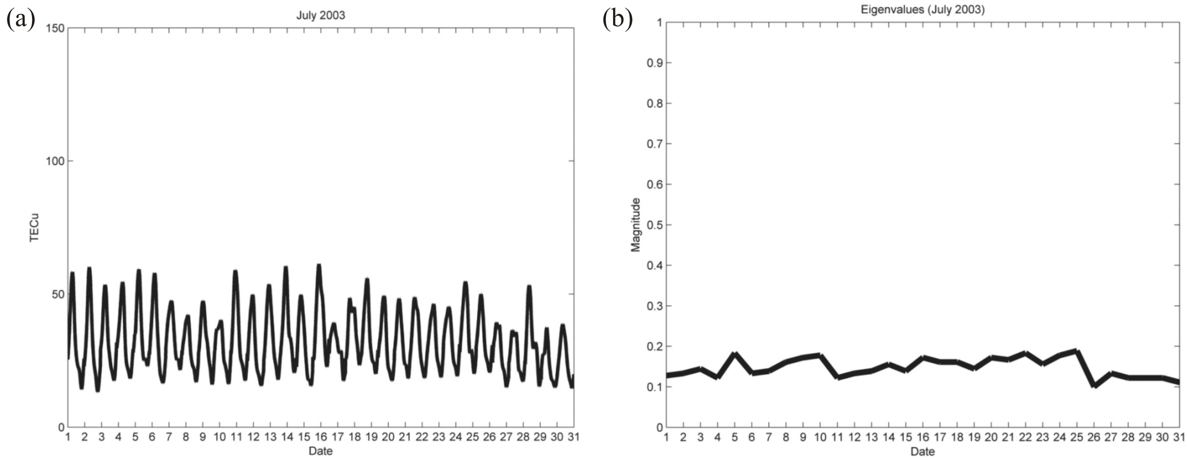

Fig. 11. (a) The figure shows the ionospheric TEC record from 1 to 31 July 2003. (b) The figure shows eigenvalues using the PCA to this ionospheric TEC record. The largest two earthquakes to occur in the research region for this month were of Richter magnitude scale M = 4.4 on 9 and 13 July.

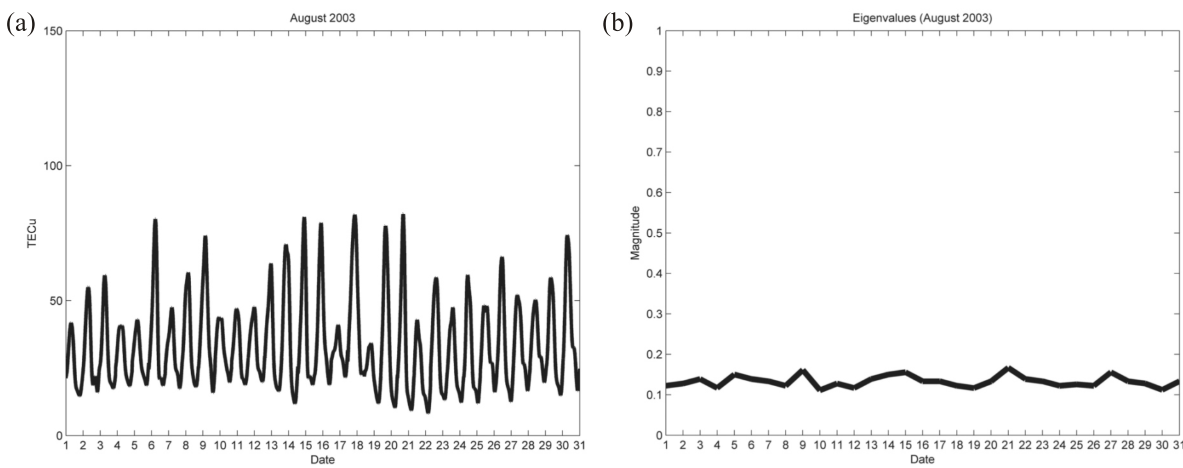

Fig. 12. (a) The figure shows the ionospheric TEC record from 1 to 31 August 2003. (b) The figure shows the eigenvalues using the PCA to this ionospheric TEC record. No earthquakes occurred in the researched region for this month.

and an earthquake (M = 4.4) on 9 July 2003 (Fig. 11) and the fact that no earthquakes occurred in August 2003, but a small extreme eigenvalue exists on 9 August (Fig. 12). The above evidence seems to indicate that for earthquakes of M < 5.0 extreme eigenvalues resulting from applying PCA to ionospheric TEC could result from earthquakes but the evidence is in no way definitive. These small extreme eigenvalues could be attributed to any number of other possible disturbances in the ionosphere such as internal ionospheric features, radio waves from the lower atmosphere, and cosmic rays (Martynenko 1989; Space Environment Topic 1994, 1999; Léna et al. 1996; Tinsley 2000; Hocke and Tsuda 2001; Eriksson et al. 2002; Sreehari and Nayar 2006; Iannotta 2007; Marusek 2007; Rozhnoi et al. 2007). In the case of larger earthquakes, however, the corresponding disturbance to the ionosphere is on a scale large enough to negate the significance of background disturbances from smaller earthquakes and other possible ionospheric disturbances. This finding shows that for larger earthquakes clear extreme eigenvalues of the PCA being applied to ionospheric TEC can act as earthquake precursors. To confirm this finding, the corresponding ionospheric TEC record for Chi-Chi, Taiwan from 1 to 25 September 1999 (UTC) is examined. Figure 13 shows this ionospheric TEC record and the corresponding eigenvalues of the PCA. Ionospheric TEC on 17, 18, and 20 September is clearly sparser than ionospheric TEC on 16 and 19 September, and these sparser days have been defined as precursors by Liu and his partners (Liu et al. 2001). The Chi-Chi earthquake occurred on 21 September 1999 (UTC) with Richter magnitude scale $M_w = 7.6$. Similarly, three clear extreme eigenvalues on 17, 18, and 20 September indicate these precursors on the 4^{th} 3^{rd}, and 1^{st} days before this earthquake, respectively, consistent with the analysis of Liu and his partners' writings in 2001.

To further confirm the validity of the PCA approach, an earthquake in Japan is examined. The precursors of the Iwate-Miyagi Nairiku earthquake in Japan that occurred on 14 June 2008 (JST) with Richter magnitude scale $M_j = 7.2$ are detected to confirm the credibility of the PCA method. Figure 14 shows the corresponding ionospheric TEC record from 1 to 24 June 2008 (JST) and the eigenvalues of the PCA. The ionospheric TEC on 9, 12, and 13 June is clearly sparser than the ionospheric TEC on 8 and 11 June. Once again, three clear extreme eigenvalues are given by PCA for the corresponding sparse TEC days. These results confirm the validity of the PCA approach in identifying earthquake precursors in ionospheric TEC. Because of the relative size of these clear extreme eigenvalues given in Figs. 13 and 14 compared to other small extreme eigenvalues found in the figures, it is evident that these values are actual precursors to the earthquakes examined and not the result of other ionospheric disturbances. It is important to note that in Figs. 13 and 14 as with Fig. 7, the precursors to aftershocks for these earthquakes are not detected by the PCA. As previously mentioned when the time interval between earthquakes is too short, the precursors of later earthquakes may be missed by the PCA.

Magnetic storms, mainly induced by X-ray solar flares,

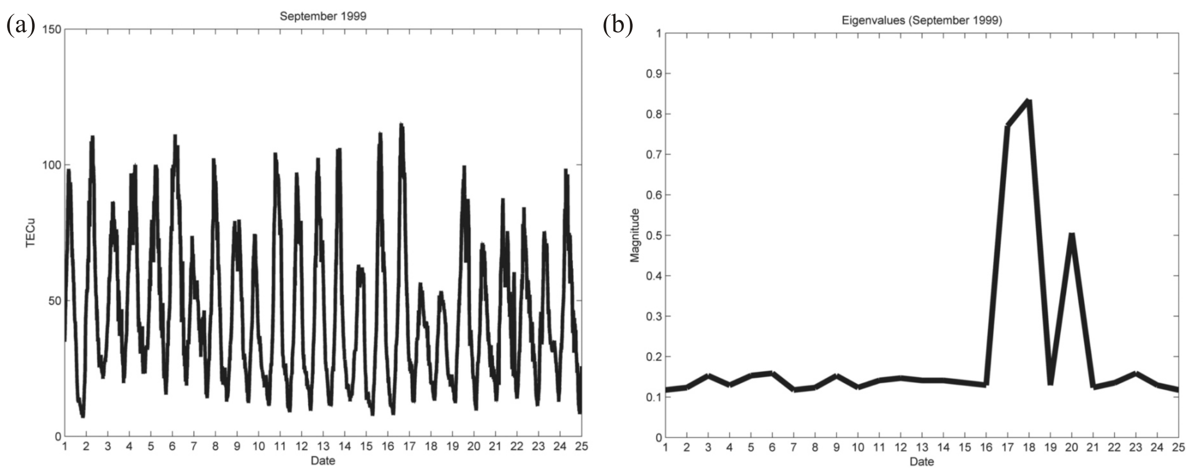

Fig. 13. (a) The figure shows the record of ionospheric total electron content (TEC) from 1 to 25 September 1999 (UTC) (data pre 15 minutes) for Chi-Chi, Taiwan (The ionospheric TEC data sources and types are the same as the ionospheric TEC data from Figs. 1 to 12). (b) The figure shows the eigenvalues using the PCA to the record of ionospheric TEC. The Chi-Chi earthquake occurred at 09:47:159 (UTC) on 21 September (marked by the circle) with Richter magnitude scale $M_w = 7.6$. Ionospheric TEC is sparser on 17, 18, and 20 September than the ionospheric TEC on 16 and 19 September (marked with arrows in Fig. 13a); they are clear anomalies and the precursors to this earthquake (Liu et al. 2001). Eigenvalues in this figure are divided by 100 to have the maximal value be between 0 and 1.

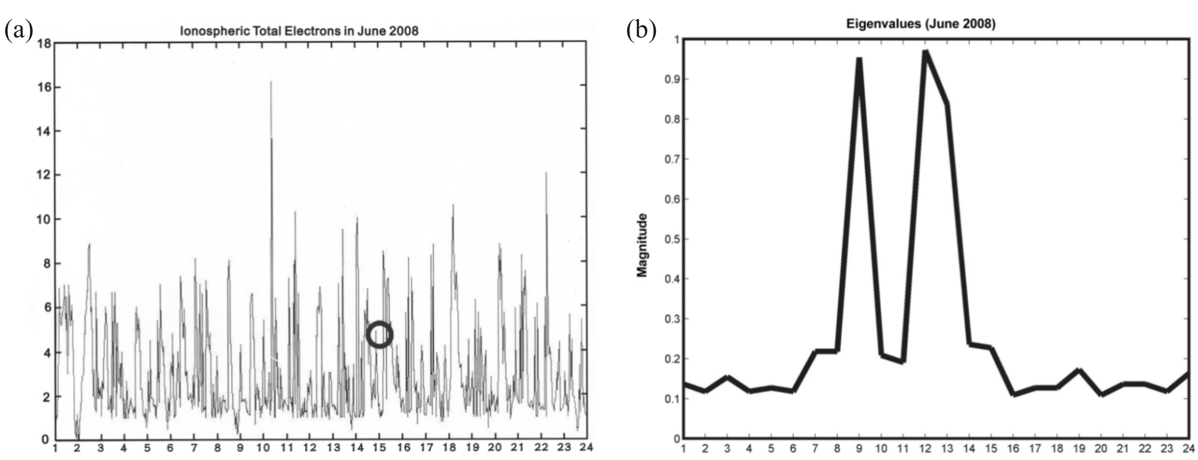

Fig. 14. (a) The figure shows the record of ionospheric total electron content (TEC) from 1 to 24 June 2008 (JST) (data pre 1 hour) (Source: the ionospheric TEC data from Japan GEONET Receiver System) in Japan. (b) The figure shows the eigenvalues using the PCA to this record of ionospheric TEC. An earthquake occurred at 08:43:00 on 14 June (JST) (marked by the circle) of Richter magnitude scale $M_j = 7.2$. Ionospheric TEC on the 1^{st}, 2^{nd}, and 5^{th} days before the earthquake was about 50% sparser than ionospheric TEC on 8 and 11 June. Note eigenvalues in this figure are divided by 10 to have the maximal value be between 0 and 1.

cause anomalous TEC behavior and also need to be considered using PCA. Figure 15 shows the X-ray flux of solar flares in the time interval from 7 to 27 January 2003. For 8 and 23 January, the intensity of corresponding X-ray fluxes are large and magnetic storms are induced causing extreme changes in ionospheric TEC data on 9 and 24 January. However, when X-ray fluxes for these dates are compared with the eigenvalues of 9 and 24 January in Fig. 4, the magnitudes of their eigenvalues are small. This result implies that magnetic storms do affect analysis results under the PCA method. Like magnetic storm, geomagnetic activity should be also considered using PCA. Kp index variances for June 2003, in which no earthquakes occurred in the researched region, are shown in Fig. 16. The magnitudes of Kp indices on June: 2, 9, 10, 17, 18, 21, 23, 24, 27, 28, 29, and 30 are larger than 4. If these results are compared with the eigenvalues of PCA in Fig. 10, the magnitudes of the correspond-

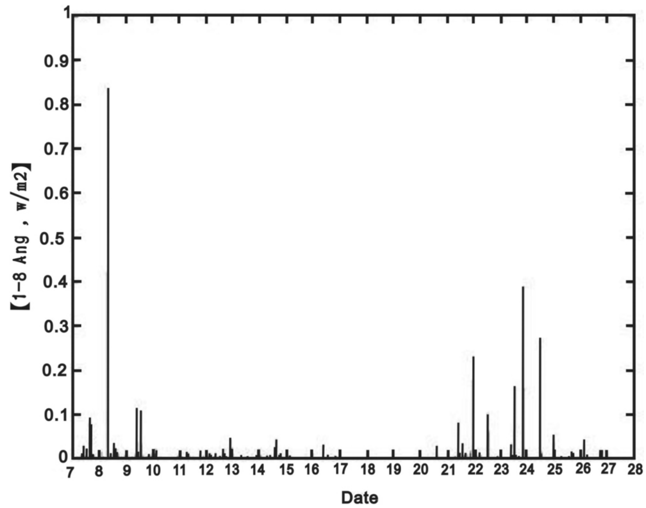

Fig. 15. This figure shows the X-ray flux of solar flares from 7 to 27 January 2003 .

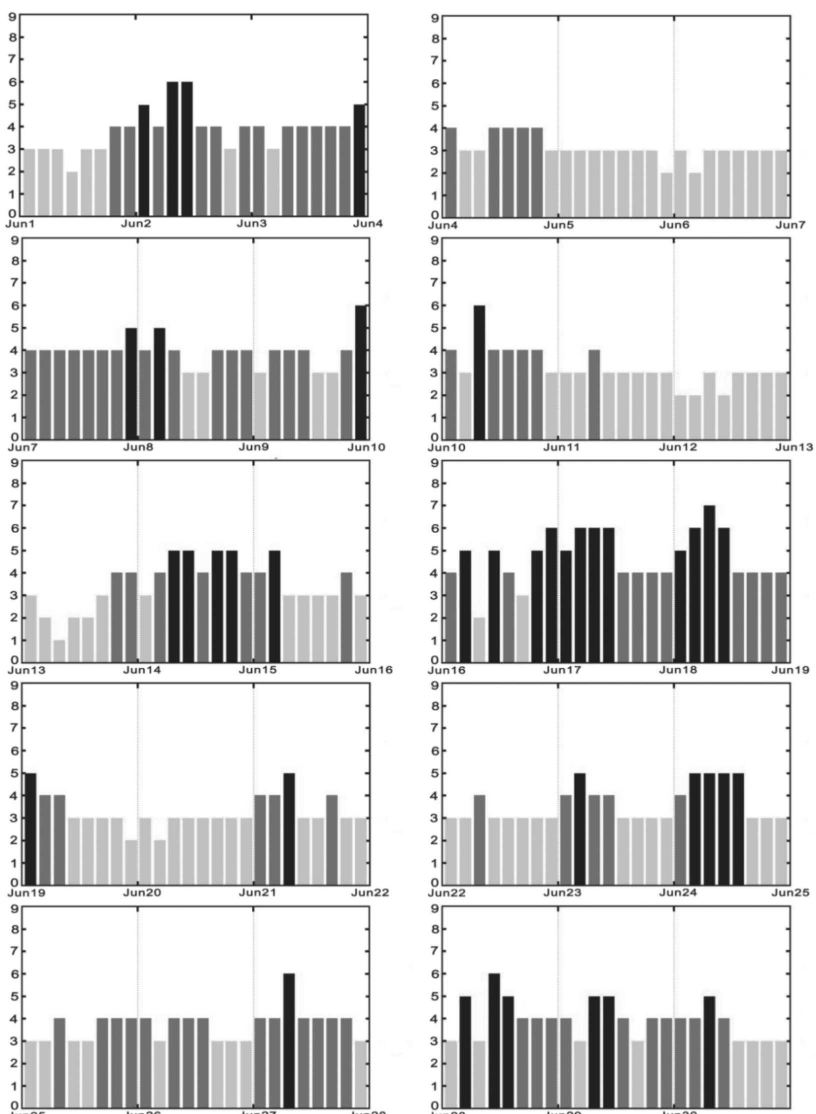

Fig. 16. This figure set denotes the Kp indices of June 2003 (UTC).

ing eigenvalues are small. Once again, such a result implies that geomagnetic activity does not affect the analysis results of the PCA method. However, advancing this area of study will require more TEC data, magnetic storm, and geomagnetic activity information.

In addition to the above, a final advantage of the PCA approach is given here. From Figs. 1 to 12, the scales of magnitude for TEC records are not normalized, but anomalies owing to earthquakes can be detected with clear extreme eigenvalues. If the records are plotted for a longer time interval, some long-term variations, such as satiation, can be revealed. Figure 17 shows TEC increasing from January to April 2002. The corresponding 12 eigenvalues of this TEC record are computed using a month-to-month basis PCA and the results are shown in Fig. 18. These long-term variances do not result in clear extreme eigenvalues, especially for the corresponding eigenvalues of June, July, and August with sparser TEC. Long-term variance is generally considered to be the result of non-earthquake related effects (e.g., solar effects). These effects on the long-term variance of TEC are not detected by PCA and there were no clear extreme eigenvalues for the period January to April 2002 because no large earthquakes occurred. This is an important point because for PCA to be successful the detection of earthquake-related TEC anomalies, given by clear extreme eigenvalues, should occur regardless of the scale normalization of TEC records. The results from Figs. 1 to 12 support this and earthquake-related TEC anomalies are detected using PCA of TEC data.

The success of PCA raises the question as to whether when processed TEC data produces clear extreme eigenvalues in real-time (when selected gain is small), they can successfully predict the onset of a large earthquake. The other issue with regards to sparse ionospheric TEC is that sparse TEC days exist in the ionosphere regardless of earthquake onset, e.g., 18 August in Fig. 12. This means that observations alone of sparse TEC ionospheric anomalies are inadequate in detecting earthquake precursors. An additional concern is that when applying PCA to one-dimensional TEC data, anomalies near the epicenter of an earthquake could not be detected. This is revealed through cross-referencing the results of this study with Pulinets' (Pulinets 2007).

There exists no certain explanation as to why ionospheric TEC becomes sparser before large earthquakes. There have been previous attempts made to explain this phenomena resulting in three theories (Liu et al. 2004): (1) The gravity theory which posits that before earthquakes occur, fine ground surface vibrations of low frequency can cause ionospheric anomalies; (2) Crustal chemistry theory which suggests that prior to earthquakes the ground vibrates and pent up gases are released from the crust to cause ionospheric anomalies; and (3) Geomagnetic and electric field theory has it that anomalous rock and magma activity near the hypocenter occurs causing rocks to deform and magma flow to slow before earthquake onset causing geomagnetic and electric field anomalies resulting in ionospheric anomalies. Whilst all these theories have merit, and sparse TEC anomalies could result from one or more of these theories, the true cause has not yet been proven. Many attempts have been made, however, including: Artru et al. (2001), Freund (2003), Chen et al. (2004), Kumar and Singh (2004), Abdu et al. (2005), Enescu (2006), Hegai et al. (2006), and Liu et al. (2006). Perhaps what is most important in terms of PCA is not the actual cause of sparse TEC anomalies, but the certainty that sparse TEC anomalies can be earthquake related and these are detectable by PCA.

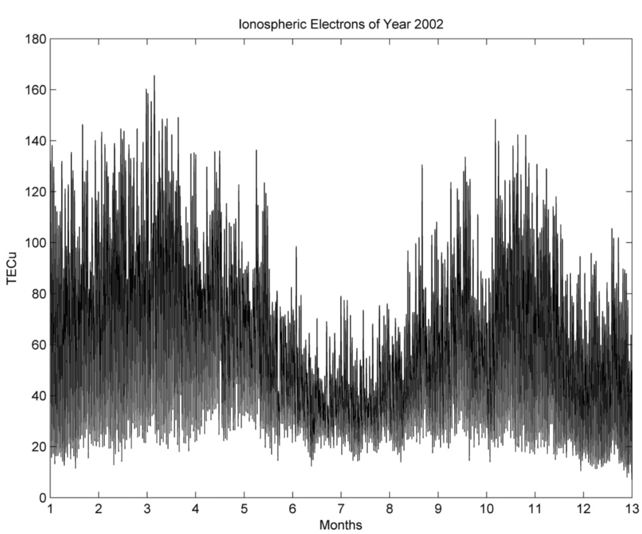

Fig. 17. This figure shows the ionospheric TEC record in 2002.

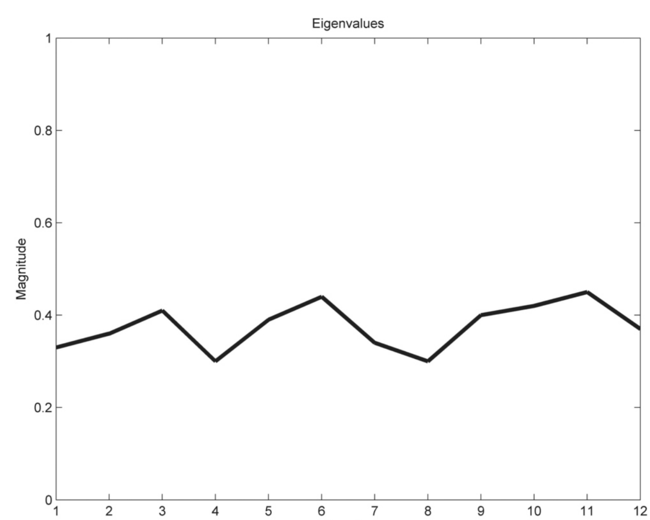

Fig. 18. This figure shows the eigenvalues using the month-to-month basis PCA to this ionospheric TEC record shown in Fig. 17. The scales of magnitude of eigenvalues are not the same as that from Figs. 1 to 12. No clear extreme eigenvalue is presented.

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