Journal of Asian Earth Sciences 114 (2015) 393–402

Contents lists available at ScienceDirect

Journal of Asian Earth Sciences

journal homepage: www.elsevier.com/locate/jseaes

Statistical evidences of seismo-ionospheric precursors applying receiver operating characteristic (ROC) curve on the GPS total electron content in China

Yuh-Ing Chen [a], Chi-Shen Huang [a,b], Jann-Yenq Liu [b,c,d,*]

[a] Institute of Statistics, National Central University, Chung-Li 320, Taiwan
[b] Institute of Space Science, National Central University, Chung-Li 320, Taiwan
[c] Center for Remote Sensing, National Central University, Chung-Li 320, Taiwan
[d] National Space Organization, HsinChu 300, Taiwan

ARTICLE INFO

Article history:
Received 31 August 2014
Received in revised form 8 March 2015
Accepted 31 May 2015
Available online 2 July 2015

Keywords:
Seismo-ionospheric precursors
Total electron content
ROC curve
Z test
AUC
Youden index

ABSTRACT

Evidence of the seismo-ionospheric precursor (SIP) is reported by statistically investigating the relationship between the total electron content (TEC) in global ionosphere map (GIM) and 56 $M \geqslant 6.0$ earthquakes during 1998–2013 in China. A median-based method together with the z test is employed to examine the TEC variations 30 days before and after the earthquake. It is found that the TEC significantly decreases 0600–1000 LT 1–6 days before the earthquake, and anomalously increases in 3 time periods of 1300–1700 LT 12–15 days; 0000–0500 LT 15–17 days; and 0500–0900 LT 22–28 days before the earthquake. The receiver operating characteristic (ROC) curve is then used to evaluate the efficiency of TEC for predicting $M \geqslant 6.0$ earthquakes in China during a specified time period. Statistical results suggest that the SIP is the significant TEC reduction in the morning period of 0600–1000 LT. The SIP is further confirmed since the area under the ROC curve is positively associated with the earthquake magnitude.

1. Introduction

Many research articles report that the seismo-ionospheric precursors (SIPs) are possibly associated with devastating earthquakes (Akhoondzadeh et al., 2010; Heki, 2011; Liu et al., 2001, 2009, 2011; Pulinets et al., 2003; Pulinets and Boyarchuk, 2004; Xia et al., 2011; Zhao et al., 2008). Statistical analyses are implemented on characteristics, such as the amount of decrease or increase, appearance local time, and duration of the SIPs in the electron density or total electron content (TEC) (Liu et al., 2000, 2004a, 2004b, 2006, 2009, 2010a, 2010b, 2013; Chen et al. 2004). For example, Liu et al. (2006) find the SIP characteristics that the electron density significantly decreases in the afternoon period 1–5 days before $M \geqslant 5.0$ earthquakes in Taiwan. Based on the results of Taiwan, Liu et al. (2009) statistically study the SIP in TEC of the global ionospheric map (GIM) (ftp://ftp.unibe.ch/aiub/CODE) associated with 35 $M \geqslant 6.0$ earthquakes cataloged by China Earthquake Administration (CEA, http://www.csndmc.ac.cn/newweb/catalog_direct_link.htm) that occurred in China during the 10-year period of 1 May 1998 to 30 April 2008, and examine the SIP related to the 12 May 2008 M8.0 Wenchuan earthquake. Liu et al. (2009) simply count earthquakes with positive and negative anomalies in GIM TEC over the epicenter, and claim the SIP with negative anomalies in 3–5 days before the earthquake. However, it is not possible to know the GIM TEC over the epicenter before the earthquake occurs. Therefore, for the practical application, Liu et al. (2013) further examine GIM TEC at a fixed location (35°N, 90°E), where is the center of 56 $M \geqslant 6.0$ earthquakes cataloged by United States Geological Survey (USGS, http://neic.usgs.gov/neis/epic/epic_global.html) in China during 1998–2012. Again, Liu et al. (2013) simply found the proportion of earthquakes with positive and negative anomalies in GIM TEC at the fixed location, and declare the SIP being negative anomalies in 2–9 days before the earthquake. The simple proportion studies result in the SIP lead times of Liu et al. (2009, 2013) been different. Therefore, a rigorous statistical study detecting SIPs is required. Recently, Wang et al. (2013) assessed the potential improvement in short-term earthquake forecasts from changes of ground deformation recorded by GPS by using Molchan's error diagram (Molchan, 1991;

* Corresponding author at: Institute of Space Science, National Central University, Chung-Li 320, Taiwan.
E-mail address: tigerjyliu@gmail.com (J.-Y. Liu).

http://dx.doi.org/10.1016/j.jseaes.2015.05.028
1367-9120/

Molchan and Kagan, 1992), which motivates us to carry out the statistical analysis examining the SIPs of GPS TEC in China.

In this study, GIM TECs are investigated for 56 $M \geqslant 6.0$ earthquakes occurred during 1998–2013 from CEA. We not only apply the z test (Neter et al., 1988) to search for the statistical significance of the anomaly defined in Liu et al. (2009), but also employ the receiver operating characteristic (ROC) curve (Swets, 1988) to study the characteristics of the SIP associated with the earthquakes in China.

2. Data analysis

Fig. 1 illustrates locations of the 56 $M \geqslant 6.0$ earthquakes (Table 1) in China during 1998–2013. For the practical application, we extract and examine the TEC at (35°N, 90°E) from the GIM during the 1–30 days before and after the earthquakes. The GIM TEC routinely published with 2-h time resolution is smoothed by using linear interpolating with a cubic spline function (de Boor, 1978) to obtain a value every 15 min. Therefore, there are 96 TEC observation points daily.

To identify possible ionospheric earthquake signatures, we compute, as usual, at each time point, the median, first and third quartiles of TEC, denoted by, $\widetilde{M}$ LQ and UQ, respectively, based on previous 15-day TECs. We then set $LB = \widetilde{M} - k(\widetilde{M} - LQ)$ and $UB = \widetilde{M} + k(UQ - \widetilde{M})$ as lower bound and upper bound, respectively, with a constant k satisfying $0 < k < \widetilde{M}/(\widetilde{M} - LQ)$. Note that Liu et al. (2009) employ $k = 1.5$ and declare a negative or positive

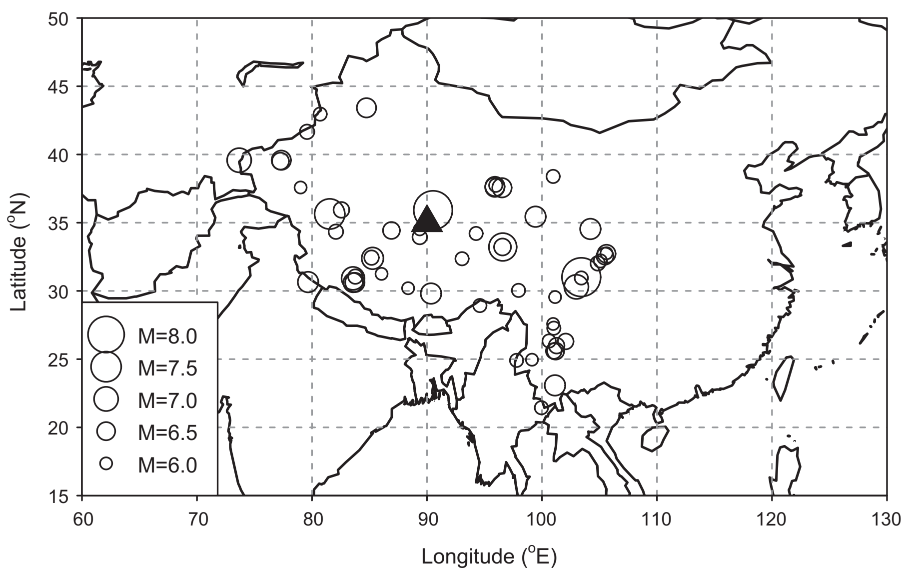

Fig. 1. Locations of the GIM TEC and the 56 $M \geqslant 6.0$ earthquakes in China during 1998–2013. The earthquake catalog is retrieved from China Earthquake Administration (http://www.csndmc.ac.cn/newweb/catalog_direct_link.htm). The triangle denote (35°N, 90°E), the location of GIM TEC used in this paper.

Table 1
$M \geqslant 6.0$ earthquakes in China during 1998–2013.

Date	Universal time	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude
1998/5/28	21:11	37.58	79.01	18	6.0
1998/7/20	1:05	30.2	88.36	31	6.0
1998/8/27	9:03	39.51	77.26	16	6.4
1998/11/19	11:38	27.27	101.03	33	6.1
1999/3/28	19:05	30.65	79.66	15	6.7
2000/1/14	23:37	25.59	101.19	32	6.4
2000/9/12	0:27	35.44	99.44	12	6.7
2001/2/23	0:09	29.55	101.14	24	6.0
2001/3/5	15:50	34.43	86.91	32	6.4
2001/4/12	10:47	24.96	99.13	4	6.0
2001/5/23	21:10	27.58	100.97	27	6.0
2001/10/27	5:35	26.33	100.62	12	6.1
2001/11/14	9:26	35.92	90.53	11	8.2
2002/6/29	6:54	34.21	94.27	22	6.1
2003/2/24	2:03	39.58	77.33	8	6.6
2003/4/17	0:48	37.56	96.52	15	6.6
2003/7/7	6:55	34.51	89.37	13	6.0
2003/7/21	15:16	25.99	101.27	10	6.3
2003/10/25	12:41	38.39	100.97	9	6.1
2003/12/1	1:38	42.96	80.71	14	6.1
2004/3/27	18:47	33.95	89.37	9	6.2
2004/7/11	23:08	30.61	83.57	18	6.6
2005/2/14	23:38	41.66	79.57	27	6.2
2005/4/7	20:04	30.62	83.73	16	6.6

Table 1 (*continued*)

Date	Universal time	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude
2005/6/1	20:06	28.93	94.6	26	6.1
2007/5/5	8:51	34.34	82.08	6	6.2
2007/6/2	21:34	23.08	101.13	6	6.7
2007/6/23	8:17	21.44	99.95	17	6.1
2008/1/9	8:26	32.39	85.27	10	6.8
2008/1/16	11:54	32.44	85.18	10	6.2
2008/3/20	22:32	35.64	81.54	21	7.5
2008/5/12	6:28	31.01	103.42	14	8.2
2008/5/13	7:07	30.95	103.42	14	6.1
2008/5/17	17:08	32.2	105.08	13	6.1
2008/5/25	8:21	32.55	105.48	14	6.4
2008/7/24	7:09	32.76	105.61	10	6.0
2008/8/1	8:32	32.02	104.85	14	6.2
2008/8/5	9:49	32.72	105.61	13	6.5
2008/8/21	12:24	24.91	97.79	14	6.1
2008/8/25	13:21	30.92	83.57	13	6.9
2008/8/30	8:30	26.3	102.06	19	6.3
2008/9/25	1:47	31.05	83.77	14	6.2
2008/10/5	15:52	39.58	73.67	27	7.0
2008/10/6	8:30	29.81	90.35	11	6.7
2008/11/10	1:21	37.66	95.91	16	6.6
2009/7/9	11:19	25.6	101.03	6	6.3
2009/7/24	3:11	31.25	86.05	13	6.0
2009/8/28	1:52	37.6	95.9	10	6.6
2009/8/31	10:15	37.74	95.98	7	6.1
2010/3/24	2:06	32.36	93.05	7	6.1
2010/4/13	23:49	33.22	96.59	14	7.3
2012/6/29	21:07	43.42	84.74	7	6.6
2012/8/12	10:47	35.94	82.56	28	6.3
2013/4/20	0:02	30.3	102.99	17	7.0
2013/7/21	23:45	34.54	104.21	15	6.7
2013/8/11	21:23	30.04	97.96	15	6.1

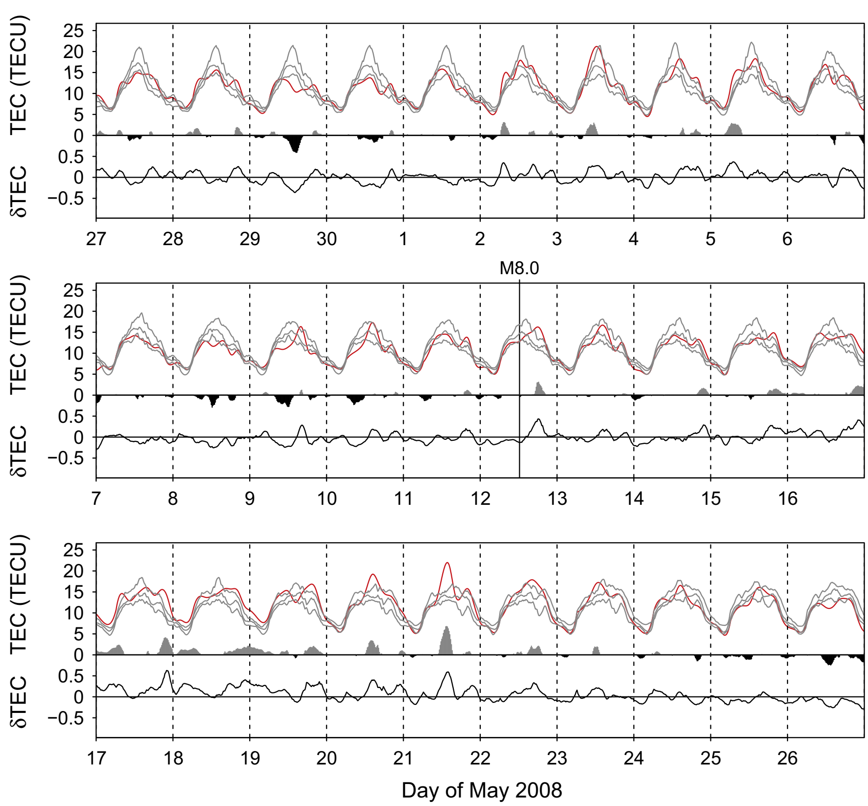

Fig. 2. Time series of GIM TEC at (35°N, 90°E) in May 2008. The red curve is the observed GPS TEC, denoted later by O. The three gray curves are the associated upper bound (UB), median, and lower bound (LB). The black curve is the δTEC. The gray and black shaded areas denote differences of O-UB and LB-O, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

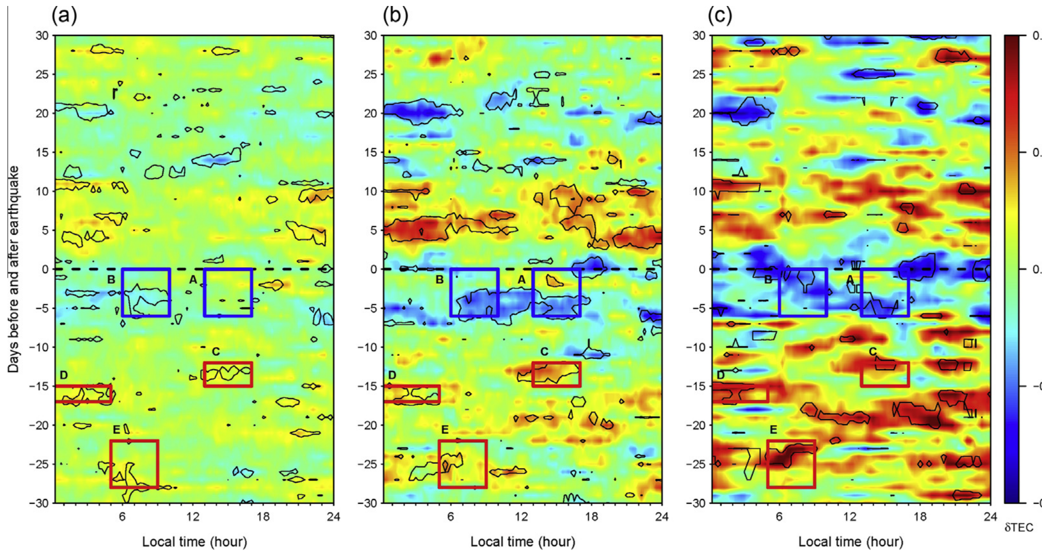

Fig. 3. The median values of δTEC in 30 days before and after earthquakes with magnitude (a) $M \geqslant 6.0$, (b) $M \geqslant 6.5$ and (c) $M \geqslant 7.0$. The contour denotes significant z test at significance level 0.05. Zones A and B are for TEC reduction, 1–6 days before earthquake, in the afternoon period 1300–1700 LT and morning period 0600–1000 LT, respectively. Zones C, D, and E are for TEC enhancement during 1300–1700 LT 12–15 days before earthquake, 0000–0500 LT 15–17 days before earthquake, and 0500–0900 LT 22–28 days before earthquake, respectively.

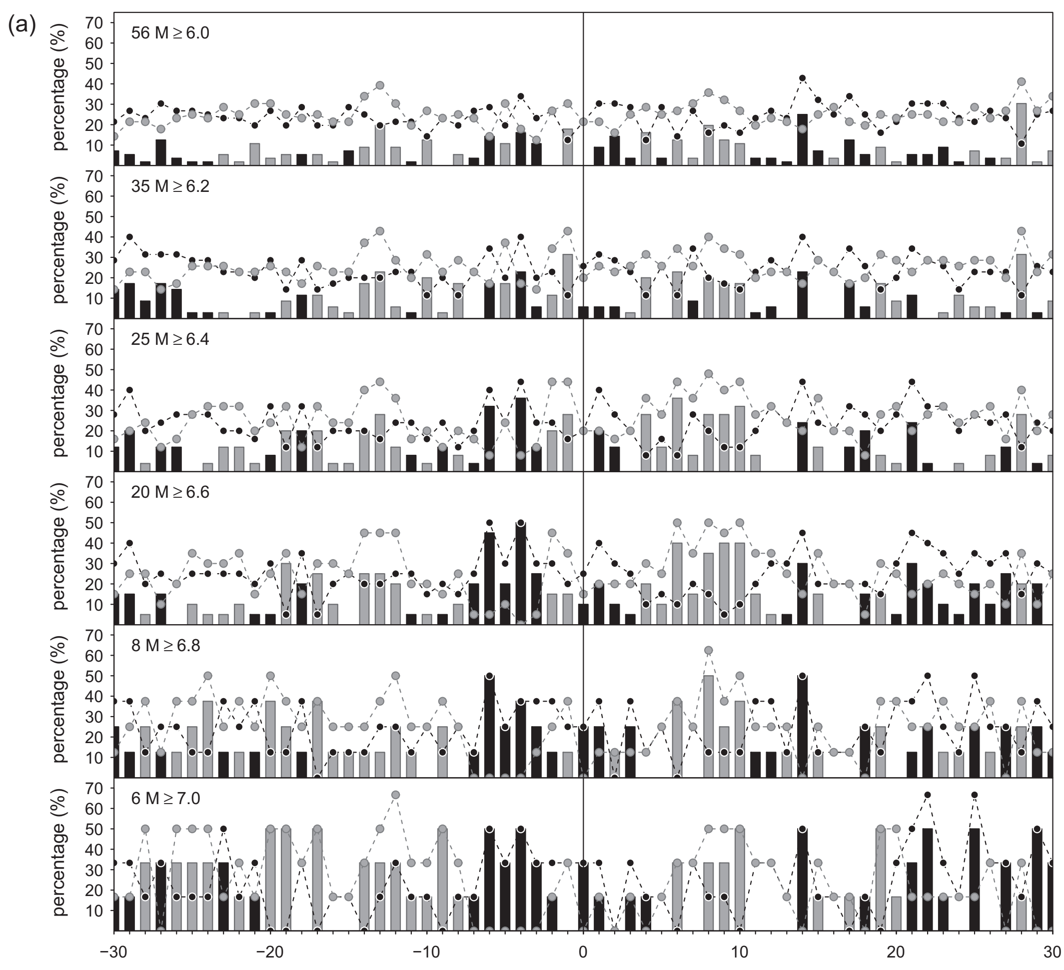

Fig. 4. Percentages of the earthquakes with negative (black dot) and positive (gray dot) precursory days that appear 30 days before and after the earthquakes in China during 1998–2013 in the (a) 1300–1700 LT, (b) 0600–1000 LT, (c) 0000–0500 LT and (d) 0500–0900 LT. The black bar represents the amount of percentage in which negative anomaly is over positive anomaly, while the gray bar denotes the amount of percentage in which positive anomaly is over negative anomaly.

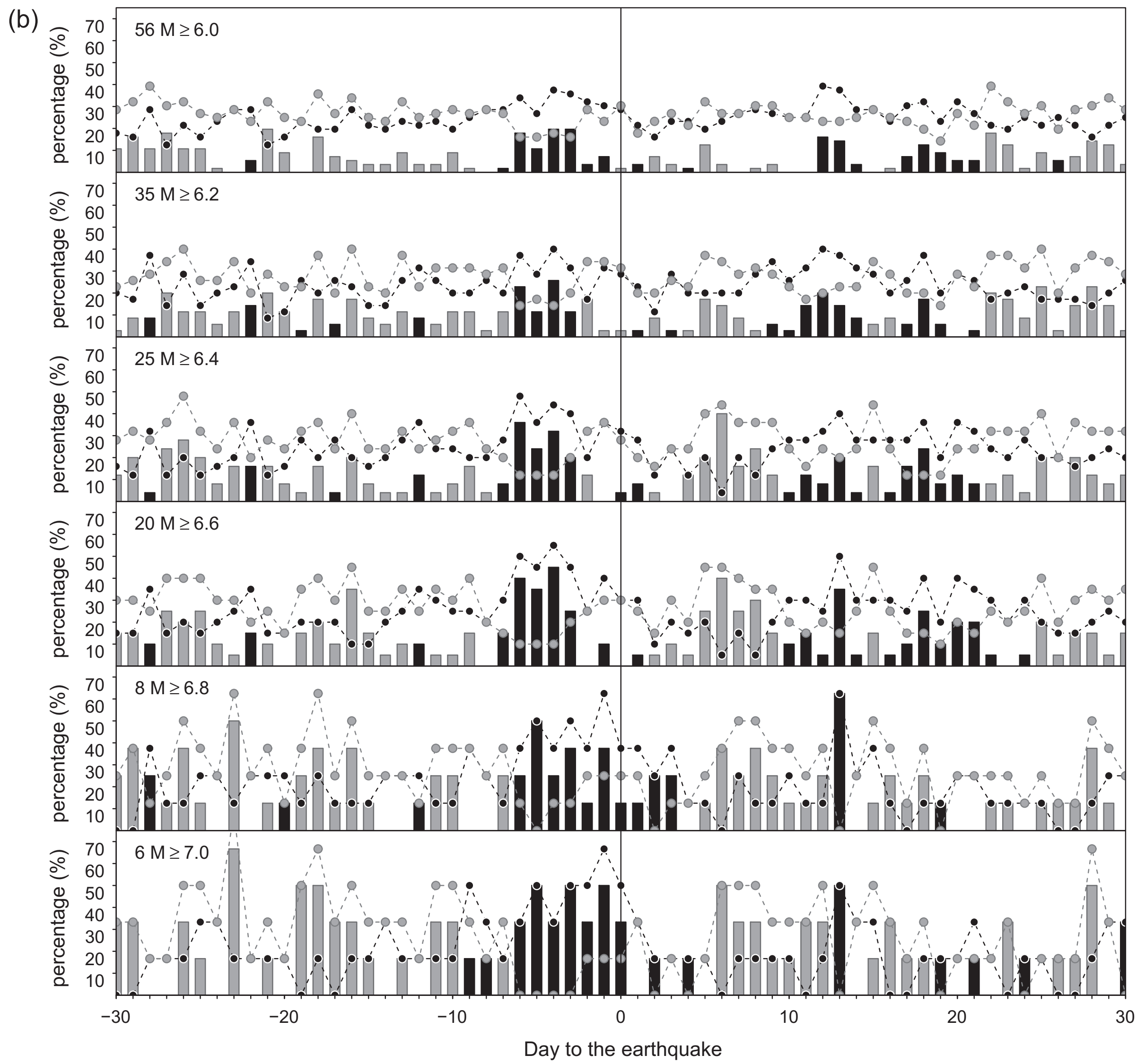

Fig. 4 (*continued*)

anomaly if an observed TEC value falls outside the associated *LB* or *UB*. They further define the negative or positive SIP for an earthquake if more than one third of negative or positive anomalies occurred in the afternoon period of 1300–1700 LT. To see the relative difference of TEC and its reference value, $\widetilde{M}$ we compute the standardized total electron content change δTEC as given by

$$\delta\text{TEC} = (\text{TEC} - \widetilde{M})/\widetilde{M}. \tag{1}$$

Then, a negative or positive anomaly occurs when $\delta\text{TEC} < -k(1 - LQ/\widetilde{M})$ or $\delta\text{TEC} > k(UQ/\widetilde{M} - 1)$.

Fig. 2 illustrates the observed TEC over the monitoring point (35°N, 90°E) for the 2008 M8.0 Wenchuan earthquake and its reference values, including the median value and the upper/lower bounds with $k = 1.5$ as well as the δTEC. The observed TEC tends to decrease in the morning period day 1–4 before the earthquake which is in a good agreement with the results in Liu et al. (2009). In general, the δTEC and anomalous TEC value exceeding the bounds are of similar tendency.

Note that the δTEC can be easily computed without specifying the cutoff value k. Therefore, we compute the median of δTEC at each time point for 1–30 days before and after the 56 $M \geqslant 6.0$, 21 $M \geqslant 6.5$, and 6 $M \geqslant 7.0$ earthquakes as displayed in Fig. 3. The δTEC median values apparently decrease 1–6 days before the earthquakes and conversely increase 10–30 days before the earthquakes.

To make a comparison with the results in Liu et al. (2009, 2013), we apply the z test with cutoff value $k = 1.5$ to find possible zones where the δTEC values are statistically significant increase or decrease. Let p be the observed proportion of earthquake-related anomalies and p_0 the background proportion of anomalies in the entire 16 years. The z value is then given by

$$z = \frac{p - p_0}{\sqrt{p_0(1 - p_0)/n}}, \tag{2}$$

where n is the number of earthquakes. If $z > 1.96$, we claim, at significant level 0.05, that $p > p_0$. The z test, or test based on z value, is conducted for negative and positive anomalies, separately.

The contours in Fig. 3 with significant z test generally depicts five zones, A–E, showing either negative or positive anomalous δTEC values. Zone A is the one studied in Liu et al. (2009) with negative anomaly during the afternoon period 1300–1700 LT 1–6 days

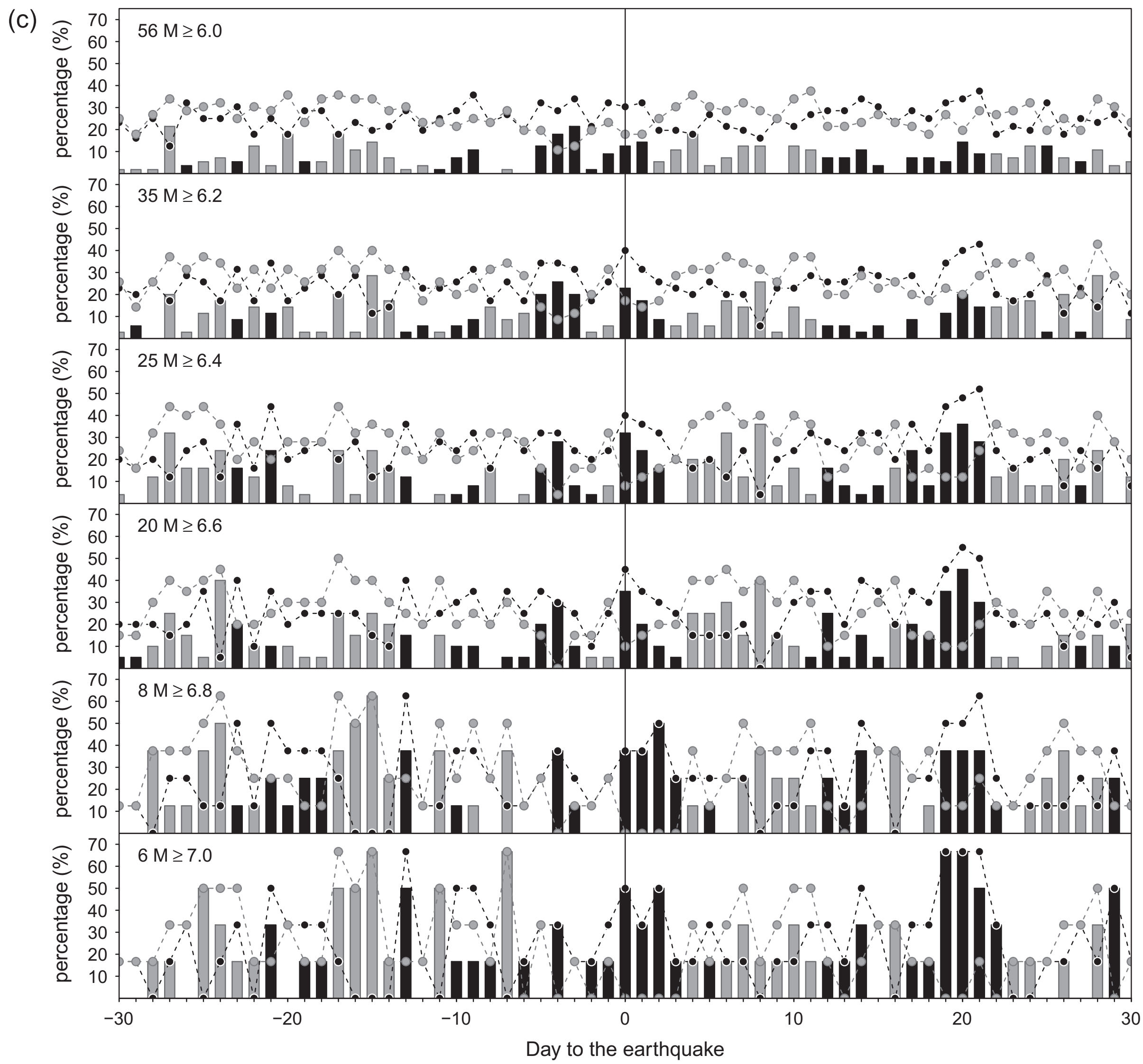

Fig. 4 (*continued*)

before earthquake. Zone B is, again, for TEC reduction 1–6 days before earthquake but in the morning period 0600–1000 LT. On the other hand, Zone C, D, and E are for TEC enhancement during 1300–1700 LT 12–15 days before earthquake, 0000–0500 LT 15–17 days before earthquake, and 0500–0900 LT 22–28 days before earthquake, respectively.

Here, we define the negative or positive precursory day in which more than one third of δTEC anomalies occurred during the specified period in each of the five zones. Fig. 4 displays the percentages of the earthquakes under study with negative and positive precursory days and shows which kind of precursor is dominated. The observed negative or positive precursors are, in general, consistent with what we have in different zones as indicated in Fig. 3.

To find whether or not the TEC is a useful earthquake precursor, we construct the ROC curve based on the δTEC. According to the precursory information from Zone B in Fig. 3, for example, if a negative precursor with a cutoff value k appears during the morning period 0600–1000 LT, earthquakes are then alarming for the following 6 days. We then compute the true positive rate (TPR) and false positive rate (FPR) accordingly, where TPR is the probability that an earthquake is successfully alarmed and FPR is the probability to make a false alarm as given by

$$\text{TPR} = (\text{No. of alarmed earthquake days})/(\text{No. of earthquake days}) \quad (3)$$

and

$$\text{FPR} = (\text{No. of alarmed non-earthquake days})/(\text{No. of non-earthquake days}) \quad (4)$$

Hence, the ROC curve with FPR as the x-axis and TPR as the y-axis is obtained for a variety of possible cutoff value of k. The area under the ROC curve (AUC) is used for assessing the effectiveness of the TEC precursor (Bradley, 1997). Note that, when TPR = FPR, an equal chance to alarm earthquake day and non-earthquake day, we have AUC = 0.5. Therefore, a precursor has to meet AUC > 0.5. However, to prevent issuing too often the false alarm for earthquakes, we prefer a small value of FPR and require TPR > FPR.

To find the significance of the observed ROC curve, a simulation-based statistical test for testing H_0 (SIPs are randomly observed) versus H_A (SIPs are not randomly observed) is performed. We randomly generate earthquake days with the observed ones during the study period, and then calculate the ROC curve and the corresponding AUC for each simulation. Based on 500

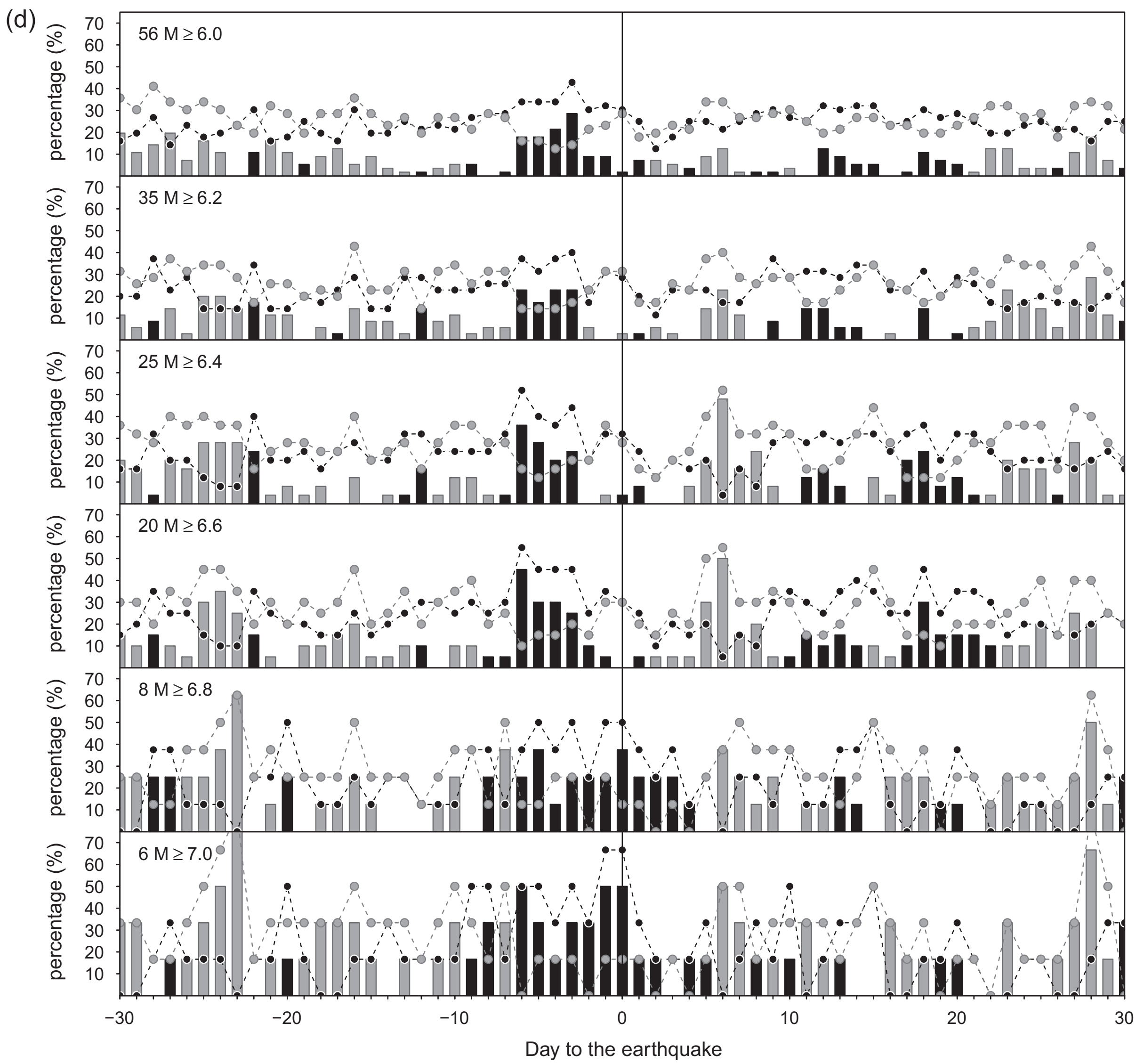

Fig. 4 (*continued*)

simulations, the p value, which is the proportion of the simulated sequences with AUC larger than the observed AUC, is obtained. Notice that the small *p* values (<0.05) lead to the rejection of the null hypothesis H_0.

Fig. 5 displays the ROC curves of the five anomalous zones for alarming earthquakes of different magnitudes. The gray curves denote the 500 ROC curves based on the simulations. The associated AUCs and p values are also reported in Table 2. It can be seen that almost all the AUCs are greater than 0.5, except that of $M \geqslant 6.0$ in Zone A. The p values less than 0.05 show that SIPs in Zone B, $M \geqslant 6.5$ in Zone C and $M \geqslant 7.0$ in Zone E are significant and useful. Note that the precursory information from Zone B is preferred for alarming $M \geqslant 7.0$ earthquakes since it has the largest AUC and preserves a smallest FPR.

Other than AUC, we can use the cutoff value-dependent R score (Shi, 2001; Chen et al., 2004) to evaluate the efficiency of SIP, where R score = TPR–FPR. In fact, we can choose an optimal cutoff value *k* to attain the maximum R score, which is called the Youden index (Youden, 1950). The optimal cutoff values of the precursory information from Zone B are $k = 3.5$ for $M \geqslant 6.0$ earthquakes and $k = 3.6$ for $M \geqslant 6.5$ or $M \geqslant 7.0$ earthquakes. Moreover, the corresponding Youden indexes are 0.17, 0.28 and 0.58 for earthquakes with $M \geqslant 6.0$, $M \geqslant 6.5$ and $M \geqslant 7.0$, respectively. In particular, for alarming $M \geqslant 7.0$ earthquakes, the Zone B-based precursor with $k = 3.6$ produces TPR = 0.83 with FPR = 0.25. On the contrary, using $k = 1.5$, the Zone B-based precursor gives TPR = 1.0, but yields a false alarm rate as FPR = 0.71.

3. Discussion and conclusion

Liu et al. (2000, 2006) find that the SIP of the ionospheric F2-peak plasma frequency foF2 appear in the afternoon period of 1200–1800 LT 5 days before 184 (13) $M \geqslant 5.0$ ($M \geqslant 6.0$) earthquakes in Taiwan during 1994–1999. Liu et al. (2004a, 2004b) also report that the SIP of the GPS TEC occur in the evening period of 1800–2200 LT 5 days prior to 20 $M \geqslant 6.0$ earthquakes in Taiwan during 1999–2002. Based on the results obtained in Taiwan, Liu et al. (2009, 2013) computed the proportions of negative and positive anomalies of the GIM TEC during the afternoon and evening period, and found that the SIP is the negative anomalies appearing 3–5 days and 2–9 days before the earthquakes in China, respectively. By contrast, this paper provides solid statistical evidence of the SIPs by means of *z*-test and ROC curve. The results in

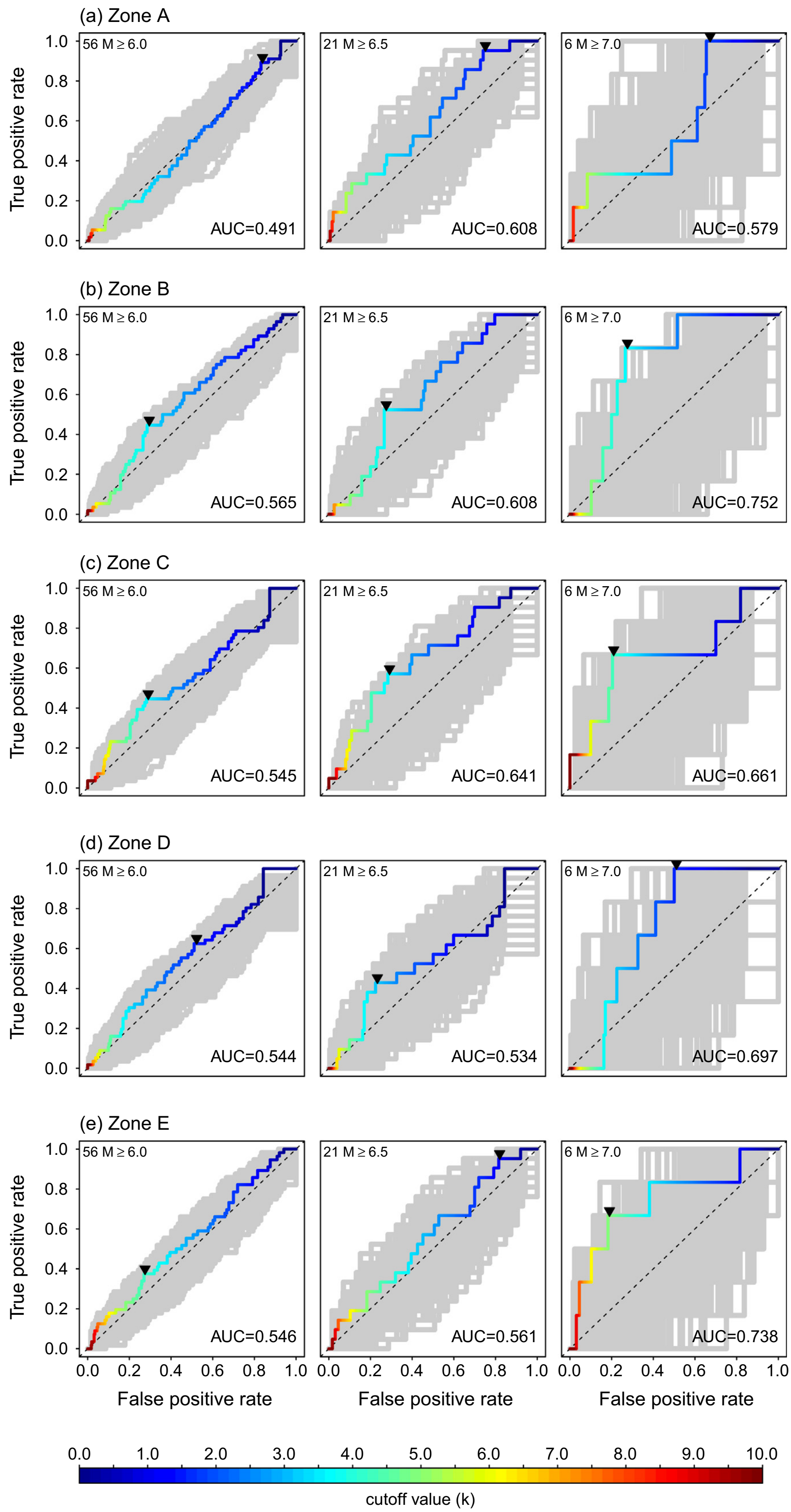

Fig. 5. ROC curves for alarming $M \geqslant 6.0$, $M \geqslant 6.5$ and $M \geqslant 7.0$ earthquakes based on precursory information from the five zones as indicated in Fig. 3. The color and gray curves denote the ROC curves of the observations and simulations, respectively. The black inverted triangle denotes the k value yielding Youden index (i.e. the greatest R score). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
AUCs in different zones.

Zone	Type of anomaly	Period	Alarming days before EQK	AUC (p value)[a]		
				$M \geqslant 6.0$	$M \geqslant 6.5$	$M \geqslant 7.0$
A	Negative	1300–1700 LT	1–6	0.491 (0.568)	0.608 (0.054)	0.579 (0.240)
B	Negative	0600–1000 LT	1–6	**0.565** (0.032)	**0.608** (0.050)	**0.752** (0.004)
C	Positive	1300–1700 LT	12–15	0.545 (0.128)	**0.641** (0.016)	0.661 (0.096)
D	Positive	0000–0500 LT	15–17	0.544 (0.114)	0.534 (0.318)	0.697 (0.060)
E	Positive	0500–0900 LT	22–28	0.546 (0.096)	0.561 (0.158)	**0.738** (0.024)

[a] The bold font denotes the significant case with p value smaller than 0.05. EQK: the earthquake.

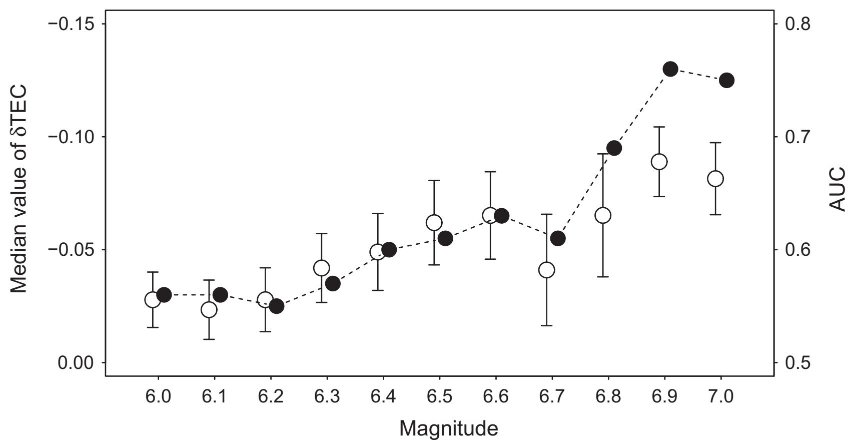

Fig. 6. The average values of δTEC medians during morning period 0600–1000 LT 1–6 days before earthquakes and the area under the associated ROC curve (AUC). The empty circle and bounds denote the average value and average value ± standard error. The solid circle is the associated AUC.

Table 2 and Fig. 5 show that SIPs in China are most likely appearing in the morning period 0600–1000 LT (Zone B), but not the afternoon period 1300–1700 LT (Zone A) or the evening period 1800–2200 LT adopted by Liu et al. (2009, 2013).

In this study, the z test at significance level 0.05 shows the SIP appears prior to 56 $M \geqslant 6.0$ earthquakes in China during 1998–2013 in the four different time/day zones. The GIM TEC reduction is observed in the morning period 0600–1000 LT/1–6 days (Zone B) and GIM TEC enhancement appears 1300–1700 LT/13–15 days (Zone C), 0000–0500 LT/15–17 days (Zone D), and 0500–0900 LT/22–28 days (Zone E). Note that for $M \geqslant 6.5$ earthquakes, Zone A (during 1300–1700/1–6 days) adopted by Liu et al. (2000, 2004a, 2004b, 2006, 2009, 2013) also becomes significant. Thus, the ROC curve is then used to evaluate the SIPs as stated in the above five zones. The ROC curves and the associated AUCs recommend that a significant TEC reduction in the morning period 0600–1000 LT on 1–6 days (Zone B) provides with a reliable SIP for $M \geqslant 6.0$ earthquakes in China. Moreover, Youden index suggests a larger cutoff value for determining anomaly bounds which helps to lower the chance of issuing false alarm for the earthquakes with different magnitudes in China. The results suggest that instead of $k = 1.5$, $k = 3.5$ should be adopted.

The statistical study confirms that SIPs of the GPS TEC in China during the morning period 0600–1000 LT are significant and reliable. To further investigate whether or not the SIP is scientific sound, we compute the median δTEC in 0600–1000 LT 1–6 days prior to each $M \geqslant 6.0$ earthquake in China. The average of δTEC medians along with its standard error are then calculated for earthquakes with different magnitudes. Fig. 6 shows that the average of δTEC medians is increasing with the associated earthquake magnitude and is closely related to the associated AUC. It implies that larger earthquakes have the greater preparation, and in turn release a stronger SIP of GPS TEC. In conclusion, the z test and ROC curve confirm that the SIP in China is the GPS TEC anomalously and significantly decreasing in the morning period 0600–1000 LT.

Acknowledgement

This study is supported by Grant MOST 103-2628-M-008-001 from the Ministry of Science and Technology (MOST) to National Central University.

References

Akhoondzadeh, M., Parrot, M., Saradjian, M.R., 2010. Electron and ion density variations before strong earthquakes ($M > 6.0$) using DEMETER and GPS data. Nat. Hazard Earth Syst. Sci. 10, 7–18.
Bradley, A.P., 1997. The use of the area under the ROC curve in the evaluation of machine learning algorithms. Pattern Recogn. 30 (7), 1145–1159.
Chen, Y.I., Liu, J.Y., Tsai, Y.B., Chen, C.S., 2004. Statistical tests for pre-earthquake ionospheric anomaly. Terr. Atmos. Ocean. Sci. 15, 385–396.
de Boor, C., 1978. A Practical Guide to Splines. Springer-Verlag.
Heki, K., 2011. Ionospheric electron enhancement preceding the 2011 Tohoku-Oki earthquake. Geophys. Res. Lett. 38, L17312. http://dx.doi.org/10.1029/2011GL047908.
Liu, J.Y., Chen, Y.I., Pulinets, S.A., Tsai, Y.B., Chuo, Y.J., 2000. Seismo-ionospheric signatures prior to $M > 6.0$ Taiwan earthquakes. Geophys. Res. Lett. 27, 3113–3116.
Liu, J.Y., Chen, Y.I., Chuo, Y.J., Tsai, H.F., 2001. Variations of ionospheric total electron content during the Chi–Chi earthquake. Geophys. Res. Lett. 28, 1383–1386.
Liu, J.Y., Chuo, Y.J., Shan, S.J., Tsai, Y.B., Chen, Y.I., Pulinets, S.A., Yu, S.B., 2004a. Pre-earthquake ionospheric anomalies registered by continuous GPS TEC measurement. Ann. Geophys. 22, 1585–1593.
Liu, J.Y., Chen, Y.I., Jhuang, H.K., Lin, Y.H., 2004b. Ionospheric foF2 and TEC anomalous days associated with $M > 5.0$ earthquakes in Taiwan during 1997–1999. Terr. Atmos. Ocean. Sci. 15, 371–383.
Liu, J.Y., Chen, Y.I., Chuo, Y.J., Chen, C.S., 2006. A statistical investigation of pre-earthquake ionospheric anomaly. J. Geophys. Res. 111, A05304. http://dx.doi.org/10.1029/2005JA011333.
Liu, J.Y., Chen, Y.I., Chen, C.H., Liu, C.Y., Chen, C.Y., Nishihashi, M., Li, J.Z., Xia, Y.Q., Oyama, K.I., Hattori, K., Lin, C.H., 2009. Seismo-ionospheric GPS total electron content anomalies observed before the 12 May 2008 Mw7.9 Wenchuan

earthquake. J. Geophys. Res. 114, A04320. http://dx.doi.org/10.1029/2008JA013698.
Liu, J.Y., Chen, Y.I., Chen, C.H., Hattori, K., 2010a. Temporal and spatial precursors in the ionospheric global positioning system (GPS) total electron content observed before the 26 December 2004 M9.3 Sumatra–Andaman Earthquake. J. Geophys. Res. 115 (A09312), 2010J. http://dx.doi.org/10.1029/A015313.
Liu, J.Y., Chen, C.H., Chen, Y.I., Yang, W.H., Oyama, K.I., Kuo, K.W., 2010b. A statistical study of ionospheric earthquake precursors monitored by using equatorial ionization anomaly of GPS TEC in Taiwan during 2001–2007. J. Asian Earth Sci. 39, 76–80.
Liu, J.Y., Le, H., Chen, Y.I., Chen, C.H., Liu, L., Wan, W., Su, Y.Z., Sun, Y.Y., Lin, C., Chen, M.Q., 2011. Observations and simulations of seismoionospheric GPS total electron content anomalies before the 12 January 2010 M7 Haiti earthquake. J. Geophys. Res. 116, A04302. http://dx.doi.org/10.1029/2010JA015704.
Liu, J.Y., Chen, C.H., Tsai, H.F., Le, H., 2013. A Statistical study on seismo-ionospheric anomalies of the total electron content for the period of 56 $M \geqslant 6.0$ earthquakes occurring in China during 1998–2012. Chin. J. Space Sci. 0254–2164/2013/33 (3), 258–269.
Molchan, G.M., 1991. Structure of optimal strategies of earthquake prediction. Tectonophysics 193, 267–276.
Molchan, G.M., Kagan, Y.Y., 1992. Earthquake prediction and its optimization. J. Geophys. Res. 97, 4823–4838.
Neter, J., Wasserman, W., Whitmore, G.A., 1988. Applied Statistics, third ed. Allyn and Bacon, Boston, MA.
Pulinets, S.A., Boyarchuk, K., 2004. Ionospheric Precursors of Earthquakes. Springer, New York.
Pulinets, S.A., Legen'ka, A.D., Gaivoronskaya, T.V., Depuev, V.Kh., 2003. Main phenomenological features of ionospheric precursors of strong earthquakes. J. Atmos. Sol.-Terr. Phys. 65, 1337–1347.
Shi, Y., Liu, J., Zhang, G., 2001. An evaluation of Chinese annual earthquake predictions, 1990–1998. J. Appl. Probab. 38A, 222–231.
Swets, J., 1988. Measuring the accuracy of diagnostic systems. Science 240, 1285–1293.
Wang, T., Zhuang, J., Kato, T., Bebbington, M., 2013. Assessing the potential improvement in short-term earthquake forecasts from incorporation of GPS data. Geophys. Res. Lett. 40, 2631–2635.
Xia, C., Yang, S., Xu, G., Zhao, B., Yu, T., 2011. Ionospheric anomalies observed by GPS TEC prior to the Qinghai-Tibet region earthquakes. Terr. Atmos. Ocean. Sci. 22, 177–185.
Youden, W., 1950. Index for rating diagnostic tests. Cancer 3, 32–35.
Zhao, B., Wang, M., Yu, T., Wan, W., Lei, J., Liu, L., Ning, B., 2008. Is an unusual large enhancement of ionospheric electron density linked with the 2008 great Wenchuan earthquake? J. Geophys. Res. 113, A11304. http://dx.doi.org/10.1029/2008JA013613.