Statistical Significance Analyses on Ionospheric Total Electron Content Related to Earthquakes

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Anomalous changes in the electron density and/or electromagnetic signals in the ionosphere before large earthquakes have been intensively studied. For the short-term earthquake prediction or forecast, it needs recognizable and reliable precursors. *Liu et al.* (2001) pioneer developing the total electron content (TEC) derived from measurements of ground-based GPS receivers and find a significant decrease of the GPS TEC in the afternoon period 1, 3, and 4 days prior to the 21 September 1999 M7.7 Chi-Chi earthquake. *Liu et al.* (2004) further conduct a statistical analysis to examine the GPS TEC and 20 M≥6.0 earthquakes in the Taiwan area from September 1999 to December 2002. Results show that the negative (i.e. decrease) TEC anomalies appear during the late afternoon and evening period of 18:00-22:00 LT (local time) 1-5 days prior to 16 out of the 20 M≥6.0 earthquakes. Moreover, the characteristic of the negative polarity (i.e. the TEC decrease), the appearance local time in the afternoon/evening period, and the 1-5 lead days of the earthquakes reached by the statistical analyses generally agree with those for the Chi-Chi earthquake. In the statistical results, 16 out of 20 earthquakes being successfully alarmed suggests that the TEC could be useful to detect pre-earthquake ionospheric anomalies (PEIAs) of large earthquakes. Many statistical methods have been applied testing characteristics of PEIAs in the GPS TEC (*Liu et al.*, 2004, 2010a) to see whether recognizable and reliable precursors exist in Taiwan. All the related statistical studies yield consistent results in the PEIA characteristic that negative anomalies frequently appear in the afternoon/evening period 1-5 days before the earthquakes under study. Therefore, the PEIAs of the ionospheric TEC are strongly suggested to be reliable seismo-ionospheric precursors (SIPs) in Taiwan.

Based on *Liu et al.* (2001, 2004), *Liu et al.* (2009) first time employ the global ionospheric map (GIM) to find the PEIA of the GPS TEC associated with 35 M≥6.0 earthquakes in China during the 10-year period of 1 May 1998 to 30 April 2008. Anomalies of the earthquakes and the 12 May 2008 M8.2 (Mw7.9) Wenchuan earthquake (30.986°N,103.364°E) show that the PEIA characteristic in China is the profound decrease of the GIM TEC in the afternoon period 3–5 days before large earthquakes. *Liu et al.* (2010b) report that PEIAs of the 26 December 2004 M9.3 Sumatra-Andaman earthquake meet the characteristic of the statistical results, which the GIM TEC around the epicenter significantly reduces during the afternoon period 1-5 days before 100 M≥6.0 earthquakes occurring in Indonesia from 1 May 1998 to 31 December 2008. By contrast, *Kon et al.* (2011) and *Liu et al.* (2013) statistically examine TEC anomalies associated with M≥6.0 earthquakes in Japan during 1998-2011 and find the PEIA characteristic to be positive anomalies significantly appearing 1–5 days before the earthquakes. These statistical results show that the PEIA characteristic (i.e. polarity, appearance local time, duration, lead day, etc.) varies in different locations. Therefore, for any monitoring area, it is essential to find whether the PEIA characteristic reached by statistical analyses is reliable SIPs or not.

Chen et al. (2015) recently investigate the GIM TEC and 56 M≥6.0 earthquakes in China during 1998-2013 by means of the z test (*Neter et al.*, 1988) and the ROC (receiver operating characteristic) curve (*Swets*, 1988). In this study, to see if SIPs exist and reliable, statistical analyses are implemented on the relationship between the GIM TEC and M≥6.0 earthquakes in Taiwan and Japan during 1998-2015. A median-based method together with z test is employed to determine the criteria and/or characteristics of TEC anomalies related to earthquakes. The ROC curve is used to compare the TEC anomaly-based method with some competitive alternatives for

predicting the earthquakes under study. When the observed SIPs are significantly earthquake-related, the regression analysis is used to find that the relationship between SIP strength and possible forthcoming earthquake magnitude.

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