Ionospheric electron content anomalies detected by a FORMOSAT-3/COSMIC empirical model before and after the Wenchuan Earthquake

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An empirical model of ionospheric electron content (IEC), based on FORMOSAT3/COSMIC (F3/C) data, is constructed in order to detect pre-earthquake anomalies. The empirical model provides IEC with four parameters of local time, season, longitude and latitude. For the first time we try to detect anomalies in the F3/C IEC by comparing the model values with observations during the 12 May 2008 Wenchuan Earthquake period. It is found that around the epicentre an IEC enhancement appears on day 3 (9 May) and sequential IEC reductions occur on day 6 to day 1 (6 to 11 May) before the earthquake.

1. Introduction

Recently, many pre-seismic ionospheric anomalies related to earthquakes have been reported by many researchers (Liu et al. 2000, 2001, 2006, Pulinets and Boyarchuk 2004, Molchanov et al. 2006, Parrot et al. 2006, Molchanov and Hayakawa 2008, Oyama et al. 2008). In particular, anomalies in the total electron content (TEC) obtained by ground based receivers have been found (Liu et al. 2001, 2004, 2009). Since TEC varies with local time (LT), season and solar activity, latitude and longitude, and geomagnetic disturbance, a reference, which reveals average features, is fundamentally needed to detect precursory phenomena possibly associated with the earthquakes. Previous studies used a 15-day running median of data recorded near the epicentres as the reference to detect the anomalies of TEC (Liu et al. 2001, 2004). Meanwhile, because the preparation of an earthquake is generally longer than 15 days, the 15-day median might have already been self-contaminated. In order to avoid the shortcomings of the local effect and contamination, a global empirical model should be constructed as a correct/suitable reference.

Six FORMOSAT-3/COSMIC (F3/C) micro satellites are at a low Earth orbit of ~800 km altitude, each satellite assembled a global positioning system (GPS) occultation experiment (GOX) payload, and derived an average of 1800 electron density profiles per day globally. GOX has an advantage in coverage of observation as compared to the TEC obtained by ground-based GPS receivers, because it could cover ocean and desert areas, where there are usually no receivers. Besides, ionospheric electron content (IEC) obtained by F3/C is more sensitive to ionospheric disturbance than GPS TEC for the study of lithosphere–atmosphere–ionosphere
coupling because it has been shown that the F2-peak electron density is more sensitive (Liu et al. 2006). In this paper, we construct a global empirical model of IEC between the F3/C satellite altitude and the ground. By comparing the model values with observations, we examine ionospheric anomalies possibly related to a large earthquake (magnitude 8.0) that occurred at 06:28 Universal Time (UT) 12 May 2008 in east Sichuan (Wenchuan), China (31.0° N, 103.4° E, depth 19 km).

2. Model F3/C

To find ionospheric anomalies associated with the targeted earthquake, based on F3/C data, a global empirical model of IEC, which is defined as integration of electron density in one occultation from the ground to 500 km, is constructed. Data of a 30-month period from 29 June 2006 to 1 November 2008 under geomagnetically quiet conditions (Dst > -30) are used to construct an F3/C ionosphere empirical model. The F3/C model can reproduce IEC values as functions of longitude, latitude, day of year (DOY), and Local Time (LT). Currently, the F3/C model does not have a parameter related to solar activity because the variation of the solar activity F10.7 is very small during 2006–2008. F10.7 below 75 occupied 68% of total occurrence. Three steps are taken to provide the F3/C model values. First of all, bins are set in longitude with 18° windows every 6° (60 nodes), latitude from -69° to 69° with 9° windows every 3° (46 nodes), LT with 1 h resolution (24 nodes) and DOY normalized by a length of year with 1/12 year resolution (12 nodes). The number of total bins is 794,880. After that, the median values are calculated in each bin. The average number of data points in a bin is about 85. Finally, model values at interesting points are calculated by cubic spline function in 4-dimensional space using median values of surrounding bins.

In order to estimate accuracies of the model, the root mean square error (RMS) during the daytime (LT = 09:00 – 16:00) under geomagnetically quiet conditions (Dst > -30) (cf. Kutiev and Marinov 2007) is calculated, which is given as:

\[ \text{RMS} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (o_i - m_i)^2} \]

where \( o_i, m_i \) and \( n \) denote the observed IEC, the modelled IEC, and the total number of data, respectively. It is found that the RMS of the F3/C model is 6.3 TECU (= 10^{16} electron m^-2). Deviations of observation from the F3/C model, which are defined as \((\text{IEC}_o - \text{IEC}_m)/\text{IEC}_m\), are also investigated, where \( \text{IEC}_o \) and \( \text{IEC}_m \) denote observed IEC and modelled IEC, respectively. The median, lower quartile and upper quartile of the deviations are 1.03, 0.89 and 1.21, respectively.

3. Observation and comparison

Figure 1 displays Dst, Kp, AU and AL (for definitions, see Schunk and Nagy (2000)) from 20 April to 31 May 2008. Sudden commencement occurred on 22 April, the subsequent main phase appeared on 23 April and the recovery phase continued towards the beginning of May. Although Kp values were almost below 4 between 1 and 6 May, the activity of the aurora sub-storms was enhanced, whose maximum AE (= AU – AL) intensity was about 700 nT. After this period, the auroral activity and Kp became very quiet from 7 to 18 May. All indices of ionospheric disturbance show very quiet conditions on the day the Wenchuan Earthquake occurred. A small aurora sub-storm was observed on 19 May and the auroral activity became active again. Dst
values showed a signature weak magnetic storm from 19 May to the end of May. A large solar flare was not observed and the solar activity, F10.7 was very stable between 66.4 and 88.6 sfu (1 sfu = 10^{-22} \text{ Wm}^{-2} \text{ Hz}^{-1}) from 20 April to 31 May 2008.

Figure 2 illustrates IEC values reproduced by the F3/C model at 14:30 LT (a), observed IEC during 13:00–16:00 LT (b) and the deviations of observation from the F3/C model (c) on 6 May 2008. As shown in figure 1, Dst and Kp show weak disturbance, but the AE index indicates a disturbance of the geomagnetic field around the auroral region on 6 May. Therefore positive deviations of IEC (enhancements of IEC) are found globally. The reduction of IEC is observed on the east side of the epicentre (33°C14’N 115°C14’E). Meanwhile, the reduction of the IEC is seen around the conjugate point of the epicentre (17°S 106°E). Comparing it with the case of 6 May (figure 2), the ionosphere on 9 May (figure 3) seems to be relatively quiet and the observed IEC values tend to reduce except to the west side of the Pacific Ocean and Asia region (figure 3(c)). Though the observation is far from the epicentre, it shows quite strong enhancement (about 42%) at 32° N 124° E (the east side of the Wenchuan Earthquake). There is no observation between the enhanced point and the epicentre. Since the Dst, Kp and AU and AL indices do not show any remarkable activity on 9 May, this enhancement might not result from the geomagnetic disturbance.

Figure 4 illustrates deviations of IEC around the epicentral latitude in the longitudinal sector 88–118° E from day 4 to 2 before the earthquake (8 to 10 May). Reductions of IEC can generally be seen around the epicentre. However, some strong enhancements of IEC (>50%) are observed on day 2 before the earthquake (9 May, early morning of 10 May in LT of the epicentre). To avoid sunrise effects at 04:00–06:00 LT, the daytime median (09:00–16:00 LT) of the deviation in the same longitudinal sector (88–108° E) of figure 4 with a 5°
The medians of deviation are disturbed by every magnetic storm. As pointed out before, the magnetic storm occurred on 22 April and subsequent auroral activity was high from 22 April to 6 May. During this period, the medians of deviation are disturbed. After this disturbed period, all geomagnetic indices show quiet conditions and the medians of deviation of IEC are within $\pm 15\%$, except around the epicentre ($8.8^\circ$ N) and its conjugate ($13^\circ$ S). Strong reductions of IEC ($>20\%$ less) are seen at higher latitude ($\sim 45^\circ$ N) of the epicentre from 6 days before the earthquake. Similar reductions in IEC are observed around the conjugate of the epicentre at $15^\circ$–$20^\circ$S between day 2 before and day 4 after the earthquake. After 19 May, the auroral activity began to enhance again. Especially, IEC responded together with enhancements of Dst and AE on 21 May, which reached $-33$ and about 700 nT, respectively. The disturbances of the ionosphere were weaker than the storm occurring on 21 April because the magnetic storm occurring on 19 May was not strong enough to disturb the ionosphere. The deviations have also been examined during the night-time. However, a clear signature has not been found.

Figure 2. Ionospheric electron content (IEC) values reproduced by the F3/C model (a), observed IEC during 13:00–16:00 LT (b) and deviations of observation from the model, which are defined as $(\text{IEC}_o - \text{IEC}_m)/\text{IEC}_m$ (c), on 6 May 2008, where IEC$_o$ and IEC$_m$ denote observed IEC and model IEC, respectively. Stars in each panel display the location of the Wenchuan Earthquake. The white line in (a) and the black lines in (b) and (c) represent the magnetic dip equator.
Figure 3. Ionospheric electron content (IEC) values reproduced by the F3/C model (a), observed IEC during 13:00–16:00 LT (b) and deviations of observation from the model, which are defined as (IEC_o–IEC_m)/IEC_m (c), on 9 May 2008, where IEC_o and IEC_m denote observed IEC and model IEC, respectively. Stars in each panel display the location of the Wenchuan Earthquake. The white line in (a) and the black lines in (b) and (c) represent the magnetic dip equator.

Figure 4. Deviation from the model defined by (IEC_o–IEC_m)/IEC_m from 8 to 11 May 2008 in the 88–118°E sector, where IEC_o and IEC_m denote the observed ionospheric electron content (IEC) and the model IEC, respectively. The dashed line denotes the epicentre latitude of the Wenchuan Earthquake. Red and blue lines denote 06:00 LT and 18:00 LT of the epicentre, respectively.
A strong enhancement of IEC at 32° N, 124° E, shown in figure 3, is found to the east of the epicentre on 9 May. Similar enhancements of differential TEC observed around the Wenchuan Earthquake are detected on day 3 (9 May) before the earthquake (Zhao et al. 2008). Simultaneously, NmF2, which is the peak density of the F2-region, obtained by ionosondes around the epicentre show enhancements (Zhao et al. 2008). Global Ionospheric Maps (GIM) TEC also demonstrates enhancement over the epicentre during 06:00–12:00 UT on 9 May (Liu et al. 2009). This fact and only one strong enhancement detected in the IEC suggest that the duration of the enhancement is very short, around 6 hours. Agreements of the enhancement of IEC with TEC of GIM and NmF2 suggest the enhanced anomaly appearing on day 3 before to be related to the Wenchuan Earthquake.

Sequential reductions of IEC (>20% less) are found from day 6 to day 1 (6 to 11 May) before the earthquake over the epicentre. Since the deviation proportion of the lower quartile in the F3/C model is about −10%, the above reductions can be declared earthquake related anomalies. Similar reductions in the GIM TEC on day 6 to day 1 (6 to 11 May) before the earthquake are reported by Liu et al. (2009) and on days 6, 3 and 2 by Jhuang et al. (2010). Once again, the results of Liu et al. (2009), Jhuang et al. (2010) and this study confirm that the ionospheric electron density in terms of GPS TEC and IEC significantly reduce from day 6 to day 1 before the earthquake over the epicentre. Although deviations of IEC from the F3/C model have been examined during the night-time, a clear signature has not been found. This fact suggests that the reduction of IEC might be seen during the daytime as reduction foF2, which is the plasma frequency at the F2 peak (Liu et al. 2006).

Meanwhile, figure 5 shows that the IEC anomalous reductions over the conjugate point of the epicentre appear between day 2 before and day 4 after the earthquake. Liu
et al. (2009) also observe simultaneous reduction anomalies of the GIM TEC at the epicentre and its conjugate point. They further suggest that the reduction anomalies of GIM TEC, spread to the east side of the epicentre, are due to the eastward $E \times B$ plasma drift of an upward electric field generated during the earthquake preparation period. The vertical electric field also produces an upward flow along the magnetic field line resulting in the TEC reduction anomalies. Note that the electric field immediately maps to the conjugate point along the magnetic field line due to the high conductivity of the ionosphere. Thus simultaneous reductions at both the epicentre and the conjugate point imply the existence of the upward electric field. Basically, the conjugate anomalies are weaker than the epicentre as shown in Liu et al. (2009). Therefore the anomaly at the conjugate point does not appear from day 6 to day 3 before the earthquake. After the large earthquake, the gravity wave generated by the large earthquake activity disturbs the ionosphere and enhances TEC (Heki and Ping 2005, Otsuka et al. 2006). The disturbance associated with the gravity wave generated by the main shock might mask the reduction of IEC over the epicentre. Enormous aftershocks following the main shock might also perturb the ionosphere. Since the gravity wave can only arrive at the ionosphere over the epicentre, the reduction of IEC at the conjugate point might still appear after the Wenchuan Earthquake.

In conclusion, the F3/C IEC empirical model was constructed and the anomalies associated with the Wenchuan Earthquake were examined by comparing the deviation of IEC measurements with the model values. The reduced anomalies of IEC are observed prior to the earthquake over the epicentre. Meanwhile, reduced anomalies were also found in the conjugate point of the epicentre. Since the 15-day running median, which is often used to detect earthquake related anomalies (Liu et al. 2000, 2001, 2006, 2009), is contaminated by the earthquake anomaly itself, it is difficult to distinguish co-seismic anomalies from the contaminations. Meanwhile, the empirical model does not have such contamination. Therefore the empirical model can also discuss the co-seismic anomaly. The results imply that the reference produced by the empirical model is a better/sensible quantity for detecting pre- and co-seismic anomalies.

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References


