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Removing Solar Radiation Based on the Empirical Mode Decomposition Method for Seismo-Ionospheric Anomaly Before the M9.0 Tohoku Earthquake*

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Abstract The ionospheric effect from solar activity can be seen as the background in the process of detecting the ionospheric precursor prior to strong earthquakes. The ionospheric variation induced by the forthcoming earthquake can be covered by the strong solar background during the period of high solar activity. The issue of how to remove the ionospheric effect from solar radiation is of outstanding significance. In this paper, a method of Empirical Mode Decomposition (EMD) is used to eliminate the solar background. As a case study, the global ionospheric map TEC before the M9.0 Tohoku earthquake on 11 March 2011 is analyzed. After the effect of solar radiation is removed using the EMD method, the precursor of the imminent earthquake is more obvious. The ionospheric anomaly had a local character and only appeared close to the earthquake epicenter while the useful signals were covered by the solar radiation background with traditional method, which implies that the EMD method is effective in eliminating solar radiation background.

Key words Ionospheric disturbances, Solar radiation, EMD method

Classified Index P 352

0 Introduction

Ionospheric perturbations caused by natural geophysical activity, such as volcanic eruption and earthquake, have been studied since the great Alaskan earthquake in 1964. Over the past several decades, the behavior of characteristic parameters representing the ionospheric condition during earthquake preparation times has been studied[1−5]. To obtain more credible results, some other scientists are devoted to finding statistical features of the ionospheric perturbations induced by earthquakes. Statistical results showed that ionospheric disturbances caused by seismic activities can be observed between several days and a few hours prior to M$\geqslant$5.0 earthquakes[6−8].

However, the ionosphere itself has high variability due to the complex coupling between ionosphere and atmosphere/magnetosphere. There is no doubt that solar activity is an important influencing factor. The regular and irregular variation of solar activity affects the chemical reactions and physical processes in ionosphere, and it strongly modulates the struc-

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ture and evolution of ionospheric state[9]. The data during the period of 27 or 15 days before the shock day are usually used to detect the ionospheric variations related to earthquakes. It is well know that 27 days is a roughly cycle of solar fluctuates. If the solar radiation flux variation has a general tendency of monotonous increase (or decrease), the ionospheric perturbations before earthquakes will be covered by the solar background. But an earthquake can happen at any moment. Hence it is urgent to find a strategy to eliminate the background. Liu *et al.*[10] counted the repeated times of TEC exceeding the bounds at each grid point to avoid solar effects. Afraimovich *et al.*[11] proposed a global factor, *i.e.* Global Electron Content (GEC) responsible for solar EUV radiation, to evaluate whether the perturbations were induced by solar activity. However, GEC repeats the variations of solar radiation $F_{10.7}$ in many cases but not always, and these methods cannot quantitatively evaluate the contribution of solar radiation.

In this paper, it is focused on how to estimate the seismo-ionospheric anomaly under a complex solar radiation scenario. As a case study, a sophisticated method of Empirical Mode Decomposition (EMD) is used to analyze ionospheric disturbance before the M9.0 Tohoku earthquake.

1 EMD Method

The method of Hilbert-Huang Transform (HHT) was proposed by Huang *et al.*[12]. For the last 200 years, Fourier analysis has been used for the analysis of time-varying data, which essentially breaks down the data into an infinite series of linear sinusoidal functions with variable coefficients. The EMD method is wholly different because the result produced by EMD is the only one that is adaptive (with no priori basis assigned) and time varying (the frequency is a function of time defined by differentiation rather than conventional analysis as in the Fourier type analysis, *e.g.* Wavelet analysis). The method has been widely used in solar activity, meteorological field, signal analysis, *etc.*[13−15]. Recently, based on the EMD method, Tsolis and Xenos[16] denoised the f_0F_2 signals to analyze ionospheric variation prior to the 6 April 2009 earthquake in Italy.

The EMD method can decompose the initial time sequence into a series of components with various frequencies, *i.e.* the IMFs (Interplanetary Magnetic Fields)[14]. These functions are obtained from the given data set, involving no priori basis. Hence, the EMD method is self-adaptive. Each IMF may be taken to be a proper mode of pulsations of signal. The amplitude of IMF can be permitted to vary, and this breaks the traditional limitation of invariable amplitude of the simple harmonic signals as the basic function in the method of Fourier transform. Thus the analysis of the signals becomes more flexible and closer to reality. The IMF is a stationary and narrow-band signal, and it is the information of the original signal on a different time scale. The detailed decomposition process is available in Ref.[12].

2 Ionospheric Anomaly Analysis by EMD

The major M9.0 Tohoku earthquake occurred at 05:46 UT on 11 March 2011. Its epicenter is located at geographic latitude 38.32° and longitude 142.37°. Different parameters characterizing the state of ionosphere and atmosphere before the shock day were investigated by many authors[17−19]. The ionospheric anomalies were well recognized as that the unusual enhancement of ionospheric electron density is limited close to the epicenter on 8 March three days before the earthquake onset. The present study is devoted to removing the effect from solar radiation variation rather than reporting ionospheric precursor of the earthquake.

Figure 1 (Modified from Ref.[18]) shows the day-to-day variation of TEC obtained from the Global Ionospheric Maps (GIMs) over the epicenter from 22 February to 12 March, 2011. During this period there was a tendency of monotonous increase in the solar $F_{10.7}$ radio flux (from 88 sfu to 155 sfu). Correspondingly, the ionospheric TEC had a continuous enhance-

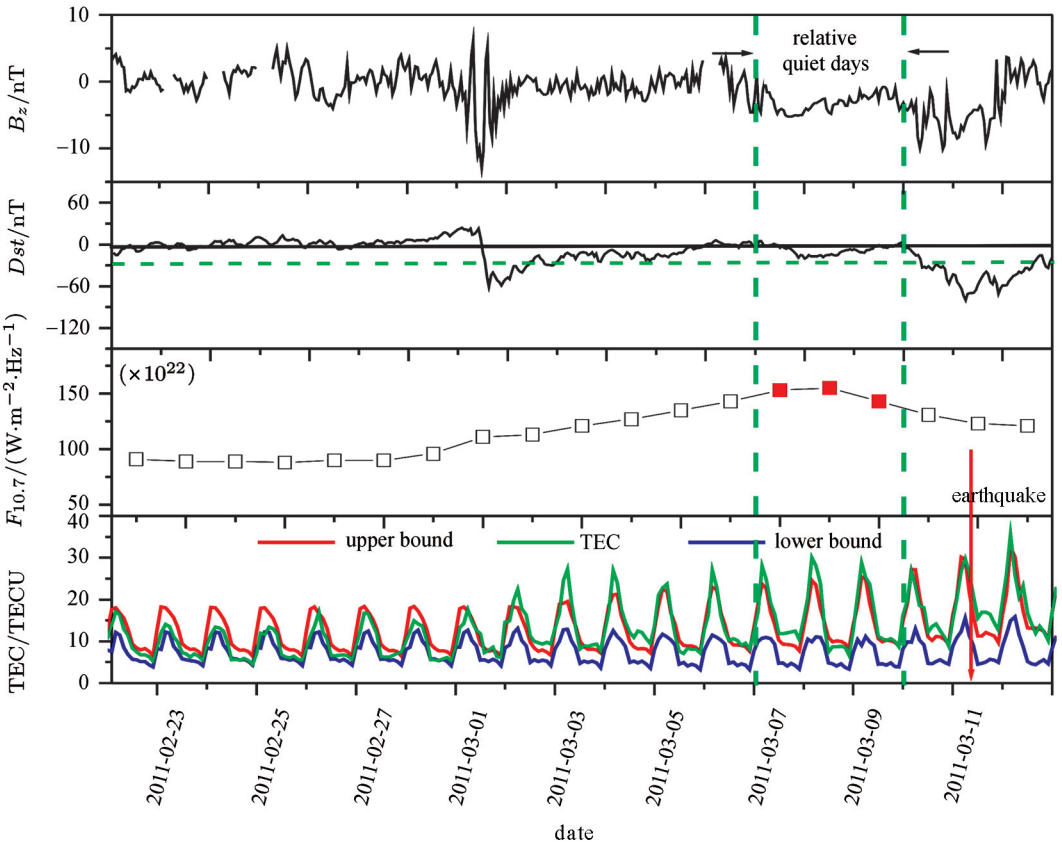


Fig. 1 Variations of IMF B_z measured from ACE satellite, Dst, $F_{10.7}$ as well as TEC right above the Tohoku epicenter extracted from the GIM. The interval between the two dashed blue lines represents the relatively geomagnetic quiet days. The red, blue and green curves denote upper/lower bound and TEC, respectively

ment. To identify the ionospheric response to earthquakes, the upper and lower bounds of the Inter-Quartile-Range (IQR)[20] are often used. However, TEC exceeded the upper bound several days due to the high solar activity in this period, which is difficult for distinguishing the precursor of the earthquake.

Using the EMD method, we analyze the TEC over the epicenter from February 22 to March 12, 2011, shown in Figure 2. It can be seen that the data is decomposed into five modes (IMF1∼IMF5) and one trend term (IMF6). IMF1 is the highest frequency component which mainly contains various noises caused by observational instruments, background noise and other factors. IMF2 is the primary component possibly corresponding to a time scale of 1 day cycle of the ionospheric variation. IMF3 is possibly containing the quasi 2-day oscillation of the ionosphere[21]. IMF4 and IMF5 are likely to the longer temporal scale oscillation induced by the planetary waves and other factors. The IMF6 is the trend term, from February 22 to March 12. It continuously increases to exceed 2 folds (from 8.9 to 19), which is consistent with the solar $F_{10.7}$ radio flux. One can obviously find that the trend term IMF6 is the primary component with amplitude of about 20 TECU, whereas the amplitudes of other modes merely are less than 10 TECU.

The solar radio flux at 10.7 cm wavelength $F_{10.7}$ is well known and commonly used to indicate the intensity of solar radiation. The index and the trend term IMF6 of ionospheric TEC obtained by the EMD method during the period are shown in Figure 3. It is obvious that there is a strong resemblance between the trends of IMF6 and $F_{10.7}$ from 22 February to

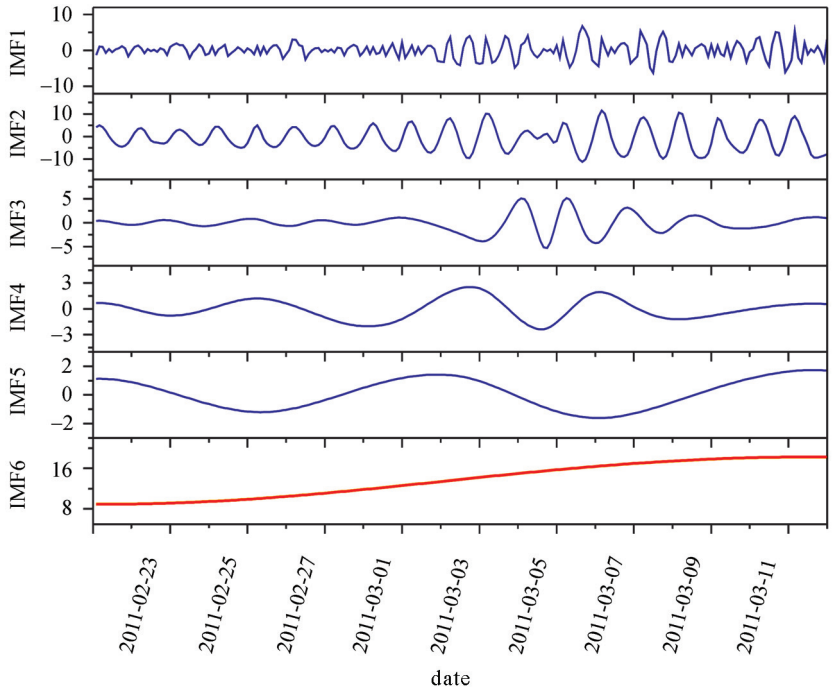


Fig. 2 IMF obtained by EMD of TEC above the epicenter of the Tohoku earthquake (TEC is the summary of IMF1∼IMF6)

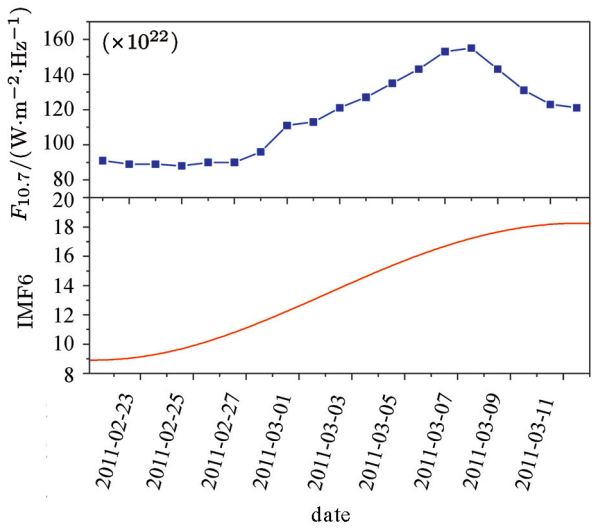


Fig. 3 10.7 cm wavelength solar radio flux ($F_{10.7}$) and the trend term (IMF6) of ionospheric TEC

8 March, which is consistent with that obtained by wavelet decomposition[19]. From March 9 to 12, the recovery phase shows the difference (2∼3 days of ionosphere reaction delay in comparison with $F_{10.7}$) what corresponds to the conclusion of Ref.[11]. In addition, the TEC enhancement induced by the magnetic storm from March 10 to 12 is another possible cause. The relationship between these two variations is checked by the linear correlation coefficient $R(= 0.8822)$. Therefore, the trend term obtained from EMD can be used to reproduce the solar radiation background from the ionospheric TEC.

As a case study, we investigate the ionospheric TEC before the Tohoku earthquake. Firstly, we use the Inter-Quartile-Range (IQR) method to analyze the TEC anomaly on March 8. Figure 4 shows the spatial distribution of the deviation of TEC from upper and lower bounds (DTEC) during 00:00 UT—22:00 UT. The pronounced enhancement area moved with the sunlit region, and unfortunately it was a global event. This phenomenon implied that this anomalous increase of TEC was partially contributed by enhanced solar radiation[18]. The ionospheric perturbation due to the earthquake was covered by the strong solar radiation background. After subtracting the ionospheric effect of solar background using EMD method, the distribution of the DTEC is shown in Figure 5. Different from Figure 4, the strong solar

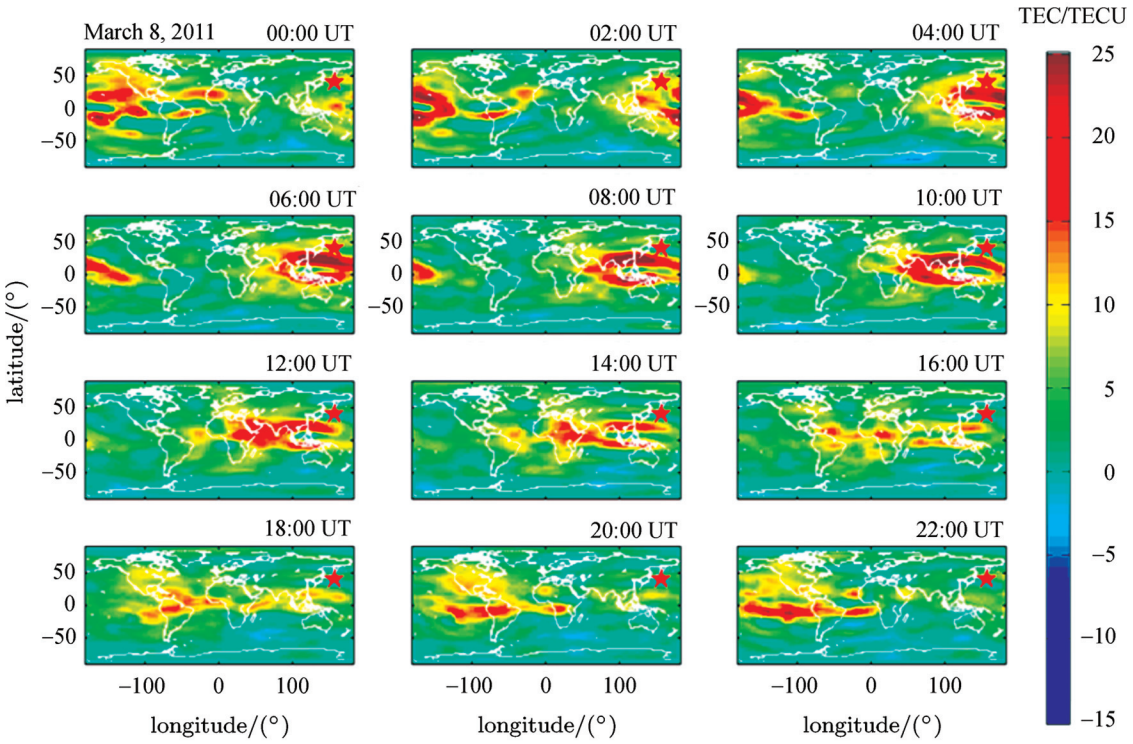


Fig. 4 Two-dimensional maps for deviation of TEC from the upper and lower bounds (DTEC) obtained by traditional method. The red star represents the epicenter

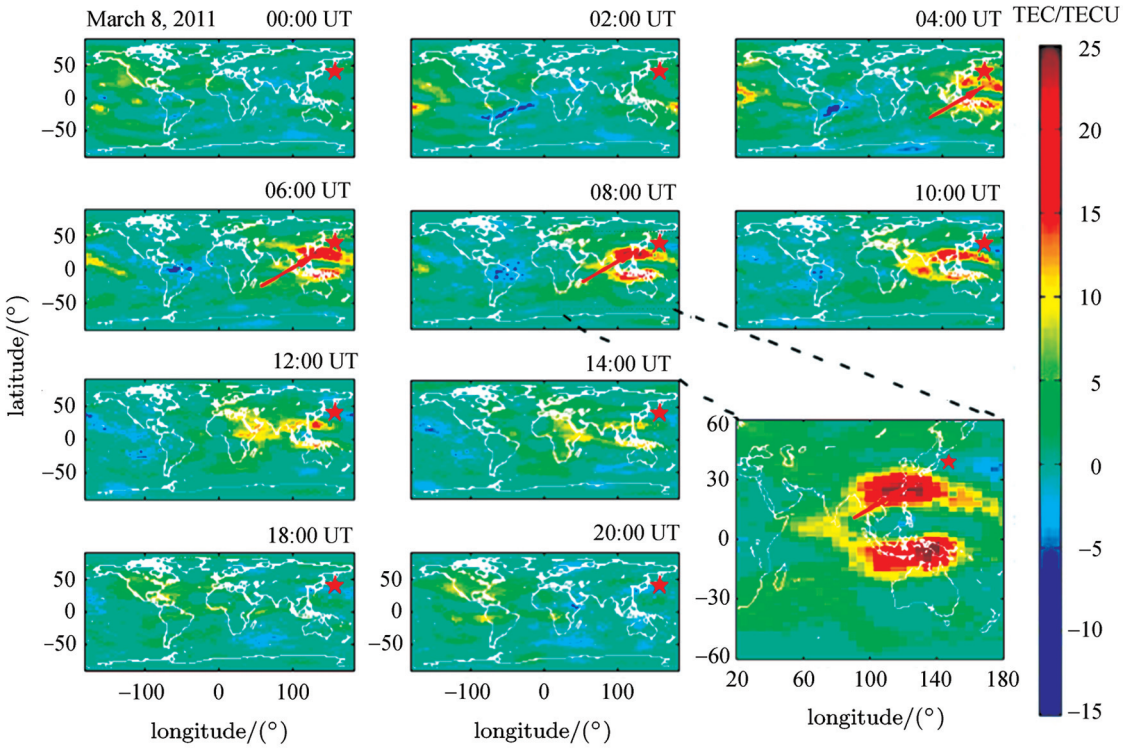


Fig. 5 Two-dimensional maps for deviation of TEC from the upper and lower bounds (DTEC) obtained by EMD method. The red star represents the epicenter. The red arrowhead line approximately denotes the enhanced region

background is almost removed. The ionospheric anomalies just appeared around the epicenter and the conjugate region. The disturbances lasted about 6 hours from 04:00 UT to 10:00 UT with a magnitude of about 25 TECU. There was still enhancement of TEC in the south of the epicenter while the sunlit region was far from the area at 10:00 UT, which can not be interpreted by the solar activity. The local character is one of the most important characteristics of the ionospheric precursors of earthquakes.

3 Discussion

Although the ionosphere behaves in a complex manner, many authors have found some ionospheric features associated with seismic events[22]. Ionospheric anomalies in Total Electron Content (TEC), critical frequency of the F_2 layer (f_0F_2) and maximum electron density of the F_2 layer (N_mF_2) were detected prior to strong earthquakes. However, these studies have paid little attention to solar radiation effect on ionospheric state. In fact, the ionospheric response to solar activity is a noise in the process of detecting the ionospheric anomalies induced by earthquakes. If the noise can be removed, the study will be more reasonable and credible.

Ideally, we can use existing ionospheric model to represent the effects of solar radiation in ionosphere. There are many different models be developed to represent the ionospheric response to solar activity variation. The International Reference Ionosphere (IRI) model is one of the widely used ionospheric models[23]. This model adopts a two-segment linear pattern to simulate the solar activity dependence of electron density without taking into account of any latitudinal, seasonal, or local time difference. Nevertheless, some works indicate that the two-segment linear pattern in the IRI model is inaccurate, and quadratic regression fit can better present the variations of the ionospheric electron density with solar indices over solar cycle timescale[9]. Therefore, this model can not represent the ionospheric variation under peculiar solar radiation level at some region.

In present study, we only focus on the advantage of EMD method in distinguishing the ionospheric precursor of the forthcoming earthquake rather than reporting the ionospheric anomaly triggered by the Tohoku earthquake. The details of the seismo-ionospheric disturbance are available in several excellent research articles[17−19]. Using this method, we analyze the ionospheric TEC before the Tohoku earthquake which occurred during a period of continuously increased solar activity. Since the well recognized ionospheric precursor appeared on March 8, we only investigate the ionospheric TEC variation on that day. After removing the solar background with the EMD method, the ionospheric anomaly had a local character and only appeared close to the earthquake preparation area, while the useful signals were covered by the solar radiation background when the traditional method was used. This result suggests the usability of the method in eliminating the solar background to detect ionospheric precursor of earthquake.

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