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Recent progress in ionospheric earthquake precursor study in China: A brief review

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A B S T R A C T

The study of ionospheric anomaly variation before large earthquakes has attracted the attention of geophysicists for many years. This is primarily because ionospheric anomaly variation has been considered to constitute one possible method to identify earthquake precursors. Since China covers several major earthquake zones, it is critical for Chinese scientists to study possible ionospheric earthquake precursors. In this report, we provide a brief summary of recent progress in the study of ionospheric earthquake precursors mainly from Chinese mainland researchers, as well as some other scientists. This report focuses on: (1) some case studies of ionospheric abnormal behaviors before some great earthquakes around the world (e.g., M7.9 Wenchuan Earthquake, M9.0 Tohoku-Oki Earthquake, M7.0 Haiti Earthquake); and (2) some statistical characteristics of ionospheric anomalies before earthquakes, including their temporal and spatial distributions, and the relationship with the forthcoming earthquake. The above-mentioned studies may provide some new and beneficial insights for the future study of ionospheric earthquake precursors.

1. Introduction

An earthquake is the result of a sudden release of energy in the Earth's crust that creates seismic waves. Earthquakes are one of the most destructive and severe natural disasters for people globally. There is, on average, about one $M \geqslant 8.0$ earthquake somewhere in the world each year, and there are 15 $M \geqslant 7.0$ earthquakes per year. Some large earthquakes have caused massive destruction recently, including: the 2004/12/26 M9.1 Northern Sumatra Earthquake, the 2005/03/28 M8.6 Northern Sumatra Earthquake, 2005/10/08 M7.6 Pakistan Earthquake, the 2008/05/12 M7.9 Wenchuan Earthquake, the 2010/01/12 M7.0 Haiti Earthquake, the 2010/02/27 M8.8 Chile Earthquake, the 2010/04/14 M6.9 Yushu Earthquake, and the 2011/03/11 M9.0 Japan Earthquake (http://earthquake.usgs.gov/earthquakes/world/world_deaths.php). Thus, the study of earthquake precursor constitutes a vital topic for geophysicists. Various types of earthquake precursors exist, such as abnormal animal behavior, radon emissions, electromagnetic variations, and ionospheric abnormal variations. Since pre-earthquake ionospheric anomalies were first discussed regarding the great Alaska earthquake as early as in 1964 (Davies and Baker, 1965; Leonard and Barnes, 1965), the study of the ionospheric abnormal variations prior to the occurrence of large earthquakes has been attracting increasing attention from geophysicists. Ionospheric anomalies before great earthquakes have also been considered to be one of the important potential ionospheric precursors. Recently, with the development of the high temporal and spatial resolution data from GPS/TEC and other satellite data, there are increasing numbers of studies on seismo-ionospheric anomalies before earthquakes (e.g., Dabas et al., 2007; Liperovsky et al., 2008; Hsiao et al., 2009; Liu et al., 2006a, 2009, 2010, 2011a; Ondon, 2009; Pulinets, 2009; Pulinets et al., 2003, 2007, 2010; Rios et al., 2004; Silina et al., 2001; Sharma et al., 2008; Sarka et al., 2007; Zakharenkova et al., 2008; Zhou et al., 2009).

Until now, there have been many theories involving lithosphere–atmosphere–ionosphere coupling to explain ionospheric abnormalities before large earthquakes. Pulinets and Boyarchuk (2004) present a detailed description of these theories. Acoustic-gravity waves and quasistatic electron fields are considered as the two principal mechanisms for ionospheric abnormal variation before earthquakes. AGW generation can be caused by several factors, such as movements of the Earth's crust, unstable thermal anomalies (rising fluids under the ground can lead to emanation of warm gases), and unstable release of lithospheric gases

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into the atmosphere (e.g., Calais and Minster, 1995; Pertsev and Shalimov, 1996; Shalimov and Gokhberg, 1998; Liu et al., 2008; Liperovsky et al., 2008; Zhao and Hao, 2015). Emissions of radioactive gas or metallic ions, such as radon, lead to increasing potential at the Earth's surface (Harrison et al., 2010), resulting in an ionization increase in the atmosphere. This then leads to an increase in the conductivity of the near-Earth atmosphere, which then causes electric field increases in the ionospheric E-region because the atmospheric impedance decreases and the total local quasi-stationary current increases. Sorokin and Hayakawa (2013) proposed a new model, which is based on the generation of currents and electric fields through the injection of charged aerosols into the atmosphere. The region of current dynamo or electromotive force (EMF) is located not in the lithosphere or in the atmosphere, but rather in the near-ground atmospheric layer. Earthquake preparation processes modify the atmosphere in this layer and form an EMF in the seismic zone. One key feature of this model is that the outgoing current includes two components, i.e., the EMF current and the conduction current. They proposed that this model can satisfactorily explain the results of quasi-static (DC) electric field observation in the ionosphere and on the ground.

The penetration of the disturbed electric field in the ionosphere could result in anomalies of ionospheric electron density both in the earthquake zone and its magnetic conjugate region (e.g., Pulinets et al., 1997; Liu et al., 2006a, 2011a; Kon et al., 2011; Le et al., 2011, 2013; Zhao et al., 2008, 2010). Recently, the disturbance in electric fields as a driving source for ionospheric anomalies before earthquakes has attracted increasing attention. Kuo et al. (2011, 2014) developed a coupling model for the lithosphere–atmosphere–ionosphere system to elucidate the electric field effect. The effects of atmospheric currents and electric fields on the ionosphere with a lithosphere current source located at various magnetic latitudes of 7.5–30° are obtained.

In this report, we provide a brief review of the recent progress made in the studies of ionospheric anomalies before large earthquakes by Chinese mainland researchers, as well as some other scientists. First, some abnormal behaviors in various ionospheric parameters before great earthquakes, such as the M7.9 Wenchuan Earthquake and the M9.0 Japan Earthquake, are briefly reported. Secondly, some results from statistical analysis are presented. Finally, one modeling study is introduced. These investigations could improve our understanding of the states of the ionosphere related to earthquake activities, and also provide new and useful insights for future studies on ionospheric earthquake precursors.

2. Case studies

2.1. M7.9 Wenchuan Earthquake

The M7.9 Wenchuan Earthquake (31.0°N, 103.4°E) on 12 May 2008, struck the eastern edge of the Tibetan Plateau at 06:28 UT, collapsing buildings and killing thousands of people in major cities along the western Sichuan Basin in China. The epicenter of the earthquake was shallow, with a depth of 19 km. The energy released by the earthquake was enormous, and tremors could be felt several thousand kilometers away from the epicenter. An anomalous enhancement in total electron content (TEC) and peak electron density of F2 layer (NmF2) was first found and reported by Chinese scientists (Zhao et al., 2008). Subsequently, there were numerous articles that focused on the ionospheric anomalies that occurred before this earthquake (e.g., He et al., 2009; Liu et al., 2009; Kakinami et al., 2010; Klimenko et al., 2011; Xu et al., 2010a,b,c; Lin, 2011; Yu et al., 2009; Zhang et al., 2009, 2010a, 2014; Zeng et al., 2009).

As shown in Fig. 1, the most striking feature is the anomalous enhancement of ionospheric electron density over Chinese stations on a geomagnetic quiet day of 9 May, 3 d prior to the earthquake. We also can find large enhancements on 2–3 May. However, this could be more likely associated with the geomagnetic storm effects. Several large geomagnetic substorms (AE: 500–1000 nT) were recorded during 1–3 May 2008. On 9 May during 06:00–12:00 UT, post-noon maximum NmF2 at station Wuhan increased by more than two times with respect to the median value. However, at Yamagawa, east of Wuhan within same geographic latitude, the increased magnitude was not as significant as that over Wuhan. At the lower-latitude station at Xiamen, daytime maximum NmF2 increased by more than 1.8 times that of the median value. At Okinawa, east and north of Xiamen, the increased magnitude was much weaker. In addition, with more ionospheric data from 10 ground-based ionosonde stations located around the epicenter with different distances, Xu et al. (2010a) found that anomalous variation of ionospheric F2-layer electron density was focused on a limited area around the earthquake's epicentral zone. Ionospheric disturbance over a limited area close to the epicenter is one of most important characteristics related to earthquakes. Moreover, it is much different from global scale disturbances caused by geomagnetic storms.

The anomalous enhancement in TEC of more than 100% was also found on 9 May (Zhao et al., 2008, 2010). At the same time, the large enhancement in TEC also occurred in the magnetic conjugated region of the epicenter. Based on data from the global ionospheric map (GIM), Liu et al. (2009) found that GPS TEC above the forthcoming epicenter anomalously decreased in the afternoon period of day 6–4 and in the late evening period of day 3 before the earthquake; whereas, it increased in the afternoon of day 3 before the earthquake.

Except for the ionospheric data from the ground-based ionosondes and GPS receivers, some other satellite data (such as FORMOSAT3/COSMIC and DEMETER) were also utilized to study abnormal variations before earthquakes (Zhang et al., 2009, 2010b, 2013; Liu et al., 2010, 2011b; Sarkar et al., 2007; Zeren et al., 2010, 2012). COSMIC data further reveal that the NmF2 significantly decreases by approximately 40%, and the hmF2 drops about 50–80 km when the GPS TEC anomalously reduces (Liu et al., 2009). Based on COSMIC data, Kakinami et al. (2010) constructed an empirical model of ionospheric electron content, which was employed to detect anomalies before earthquakes. The model results show that an electron density enhancement appears on 9 May, with sequential reductions on 6–11 May. Meanwhile, reduced anomalies were also identified in the conjugate point of the epicenter.

Based on topside ionospheric electron density data from the DEMETER satellite at an altitude of ~660 km, some researchers analyzed the electron density variations in the topside ionosphere before the Wenchuan Earthquake (Zhang et al., 2009, 2010a, 2012a; Liu et al., 2010, 2011b). The results showed that, on 9 May, the O^+ density reached its lowest values, the electron density reduced above the northeast epicenter area, and the peak values moved to the equator. In addition, the ion temperature was found with fast short-term regional anomalies at nighttime on 9 May. The variation of H^+ and He^+ was found to be different from that of O^+. The observed results demonstrate that there are no significant anomalies in the density of H^+ and He^+. It seems that the topside O^+ density variation detected by DEMETER is not consistent with the variations in F2 peak electron density and total electron content. It should be noted that, due to the specific orbit, DEMETER observations were always conducted at about 22:30 and 10:30 local time. However, the significant ionospheric anomaly in TEC and NmF2 on 9 May appeared from 12:00 local time to 20:00 local time (Zhao et al., 2008). In addition, there is no enhancement in