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Ionospheric precursors to large earthquakes: A case study of the 2011 Japanese Tohoku Earthquake

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ABSTRACT

Researchers have reported ionospheric electron distribution abnormalities, such as electron density enhancements and/or depletions, that they claimed were related to forthcoming earthquakes. In this study, the Tohoku earthquake is examined using ionosonde data to establish whether any otherwise unexplained ionospheric anomalies were detected in the days and hours prior to the event. As the choices for the ionospheric baseline are generally different between previous works, three separate baselines for the peak plasma frequency of the F2 layer, foF2, are employed here; the running 30-day median (commonly used in other works), the International Reference Ionosphere (IRI) model and the Thermosphere Ionosphere Electrodynamic General Circulation Model (TIE-GCM). It is demonstrated that the classification of an ionospheric perturbation is heavily reliant on the baseline used, with the 30-day median, the IRI and the TIE-GCM generally underestimating, approximately describing and overestimating the measured foF2, respectively, in the 1-month period leading up to the earthquake. A detailed analysis of the ionospheric variability in the 3 days before the earthquake is then undertaken, where a simultaneous increase in foF2 and the Es layer peak plasma frequency, foEs, relative to the 30-day median was observed within 1 h before the earthquake. A statistical search for similar simultaneous foF2 and foEs increases in 6 years of data revealed that this feature has been observed on many other occasions without related seismic activity. Therefore, it is concluded that one cannot confidently use this type of ionospheric perturbation to predict an impending earthquake. It is suggested that in order to achieve significant progress in our understanding of seismo-ionospheric coupling, better account must be taken of other known sources of ionospheric variability in addition to solar and geomagnetic activity, such as the thermospheric coupling.

1. Introduction

In recent years, many researchers have reported observations of ionospheric anomalies prior to large seismic events (e.g. Pulinets et al., 2003, and references therein). However, the process of separating what is deemed to be "normal" ionospheric behavior from that which might be attributed to an "earthquake preparation zone" (Dobrovolsky et al., 1979) (or "EPZ", a term adopted here because of its use in the arguments of previous works) is very complicated, as there are significant gaps in our understanding of the sources of ionospheric day-to-day variability (e.g. Rishbeth, 2006; Rishbeth et al., 2009, and references therein). It should be pointed out that co-seismic ionospheric effects, such as acoustic gravity waves that have been excited by earthquake activity, have been well established in the literature (e.g. Tsugawa et al., 2011, and references therein), but these effects form a separate issue from ionospheric precursors that are investigated in this work.

In the literature, the descriptions of pre-earthquake ionospheric anomalies can vary significantly from study-to-study. These anomalies have been found to be either negative or positive departures with respect to the background ionosphere, which is often represented by a running median over a specified number of days prior (usually between 15 and 30 days) for that particular local time (LT). To gauge how "anomalous" the ionospheric features were in these studies, a variety of statistical quantities have been estimated assuming a normal distribution; e.g. the standard deviation by Le et al. (2011), 1.5 × the upper and lower quartiles by Liu et al. (2009), the interquartile range (IQR) by Liu et al. (2004) and the semi-IQR by Liu et al. (2006). These anomalies have been reported to be observed mostly within 1–5 days before a large earthquake (e.g. Liu et al., 2004, 2009), although some

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studies have reported earthquake-related anomalies up to 34 days prior to the event (Perrone et al., 2010). In a recent study, an enhancement in the total electron content (TEC) ~40 min prior to the magnitude 9.0 Tohoku earthquake off the east coast of Honshu, Japan on 11 March 2011 was reported using Global Positioning System (GPS) receivers (Heki, 2011).

Ionospheric variability is currently attributed to three possible sources; (1) variations in solar ionizing flux, (2) geomagnetic disturbances and (3) “other” or “meteorological” influences (e.g. Forbes et al., 2000; Rishbeth and Mendillo, 2001; Mendillo et al., 2002; Rishbeth, 2006). Geomagnetic storms can either cause widespread electron density enhancements or depletions (also referred to as positive and negative ionospheric storms, respectively) depending on the time and location (see review by Mendillo, 2006), and hence cause increased ionospheric variability. The third source of variability, which is thought to be at least comparable to the effect of geomagnetic activity (Rishbeth and Mendillo, 2001), has been tentatively called “meteorological”, as it is thought that waves or electric fields from the lower or middle altitudes influence the thermospheric contributions to ionization (Rishbeth et al., 2009), via changes in composition or electrodynamic drift (Rishbeth, 2006). While ionospheric precursor studies have typically eliminated geomagnetic activity as the cause of a particular anomaly, possible changes in the thermospheric contributions are harder to quantify and may have been overlooked or under-estimated.

1.1. The Tohoku earthquake

The recent magnitude 9.0 Tohoku earthquake took place off the east coast of the Japanese main island, Honshu (38.30°N, 142.37°E), at 0546 UT on 11 March 2011. The epicenter of this earthquake is shown in Fig. 1 with the locations of the Wakkanai (45.16°N, 141.75°E), Kokubunji (35.71°N, 139.49°E) and Yamagawa (31.20°N, 128.15°E) ionosonde stations used in this analysis. The distances of the Wakkanai, Kokubunji and Yamagawa stations from the epicenter are 760 km, 390 km and 1330 km, respectively. Prior to this seismic event, a magnitude 7.3 foreshock took place at 0245 UT on 9 March 2011 at a location very close to that of the primary event, Fig. 1.

In this study, the Yamagawa, Kokubunji and Wakkanai ionosonde data is examined in the context of the observed solar and geomagnetic activity levels in the month prior to the Tohoku earthquake. The goal is to employ multiple ionospheric baselines,

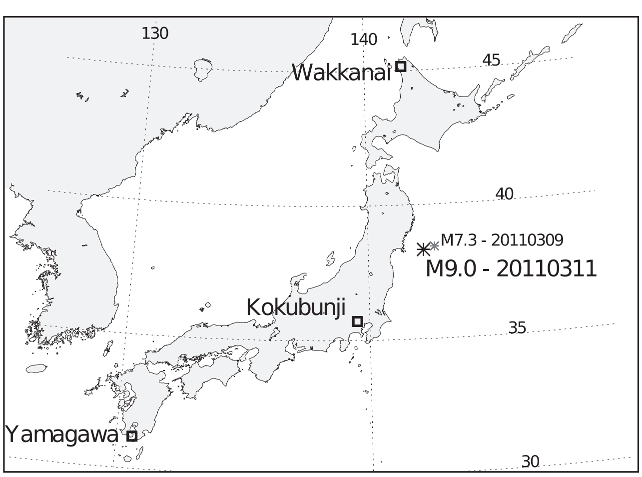

Fig. 1. The location of the M 9.0 earthquake epicenter that occurred on March 11, 2011 is shown by the large black asterisk, and the locations of the ionosondes are indicated by the squares. The location of the March 9, 2011 M 7.3 foreshock is also shown by the smaller gray asterisk.

using both statistical and physics-based models, in a search for anomalous ionospheric features, and if present, attempt to identify their physical sources. This examination consists of two parts: (1) an analysis of the full month prior to the earthquake; and (2) a more detailed presentation of the 3-day period leading up to the earthquake.

2. Observations

2.1. Overview of geomagnetic activity

It is well known that the ionosphere is highly variable, with driving forces from both above and below (e.g. Forbes et al., 2000; Mendillo et al., 2002; Rishbeth and Mendillo, 2001). So, before analyzing the ionospheric observations leading up to the earthquake, it is important to examine the geomagnetic and solar activity for this period. Fig. 2 shows the solar F10.7 radio flux, the geomagnetic activity indices Kp and Sym-H (a high-resolution 1-min version of the hourly Dst index, Wanliss and Showalter, 2006), and the auroral electrojet (AE) index. It is clear from Fig. 2 that the period leading up to the earthquake consists of a number of minor disturbances on 14 February, 18 February, and 1 March (Kp and Sym-H), in addition to related substorm activity (AE). Also noted is the maximum in solar activity on 8 March (F10.7 solar flux). One important feature to point out is the geomagnetic disturbance that peaked in intensity on the day of the earthquake; Sym-H reached −92 nT at 0525 UT, 21 mins before the earthquake.

2.2. Ionospheric baselines

Three ionospheric baselines for the ionospheric parameters were used to investigate their consistency in identifying anomalous ionospheric behavior. As many previous works have employed running hourly medians, the running 30-day hourly median, which used the previous 30 days of data for each hour, was used. In addition, the International Reference Ionosphere (IRI-2007) model (Bilitza and Reinisch, 2007) was used with the ap index, 12-month sunspot number and the daily F10.7 flux

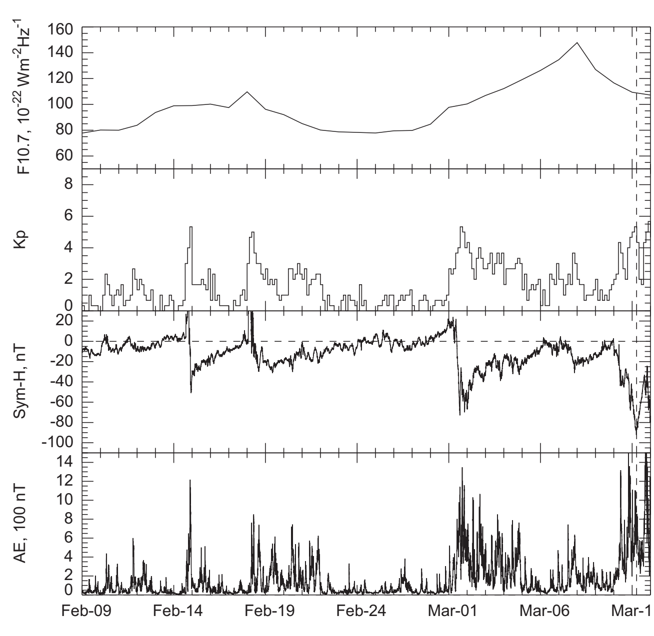

Fig. 2. Summary of the geomagnetic conditions for the 30 days prior to the 11 March 2011 earthquake. The time of the earthquake is indicated by the vertical dashed line.