Seismo-traveling ionospheric disturbances of ionograms observed during the 2011 M_w 9.0 Tohoku Earthquake

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In this paper, sequences of ionograms recorded by 4 ionosondes in Japan and 1 in Taiwan are employed to examine seismo traveling ionospheric disturbances (STIDs) triggered by the 11 March, 2011, M 9.0 Tohoku Earthquake. The circle method, a standard/traditional technique of seismologists for locating an earthquake, is used to find the origin and compute the propagation speed of the triggered STID. Results show that the STID speeds induced by Rayleigh waves, acoustic gravity waves mainly traveling in the ionosphere, and tsunami waves of the Tohoku Earthquake are 2100–3200 m/s (2.1–3.2 km/s), 900 m/s, and 200 m/s (720 km/hr), respectively. The origins derived by the circle method near the epicenter confirm that the observed STIDs were triggered by the seismic waves and tsunami waves of the Tohoku Earthquake.

Key words: Tohoku Earthquake, seismo-traveling ionospheric disturbances, ionosonde.

1. Introduction

During earthquake occurrences, vertical motions of the Earth's surface create mechanical disturbances (acoustic gravity waves; AGWs) in the neutral atmosphere, which propagate into the ionosphere and interact with the ionized gas (hereafter, seismo traveling ionospheric disturbance; STID) (Davies, 1990). An ionosonde is the most traditional instrument for probing the ionosphere, which has been routinely (every 15 minutes) recording ionograms to monitor the vertical distribution of the electron density from 90 km altitude to the ionospheric F_2 peak (about 250–350 km altitude) since the early 1930s (Hansucker, 1991). Leonard and Barnes (1965) first observed ionospheric disturbances induced by the 27 March, 1964, M 9.2 Alaskan earthquake using data at four sites of ionosondes in Alaska and California. Although fluctuated traces in the ionograms of the ionosondes were observed after the Alaskan earthquake, the origin and the propagation of the STIDs were not studied in detail.

The method of intersecting circles (hereafter, the circle method) might be the first used for locating the hypocenter (source, or epicenter) of an earthquake (Lay and Wallace, 1995). Seismologists calculate the possible circular distance (zone) to the source of seismic waves from each station, which is equal to the product of the propagation speed and the traveling time. When circular zones of three or more stations intersect at the same location, we then consider the source as being located. The short-coming of this method is that the onset time of the earthquake and the prop-

agation speed of the seismic waves should be approximately known and/or estimated in advanced.

Liu *et al.* (2006) for the first time, applied the circle method (Lay and Wallace, 1995) on ionograms recorded by 3 ionosonde stations and found the origin and propagation speed of STIDs associated with atmospheric AGWs triggered by the 26 December, 2004, M 9.3 Sumatra earthquake and/or the associated tsunami. In this paper, we employ the circle method (Lay and Wallace, 1995) to analyze ionograms recorded by 5 ionosondes, 4 in Japan and 1 in Taiwan, (Fig. 1) to locate the sources and estimate the propagation speeds of various STIDs induced by the 11 March, 2011, M 9.0 Tohoku Earthquake.

2. Observation and Results

A magnitude M 9.0 earthquake report by the U.S. Geological Survey gives its origin time as 05:46:23 UTC; the epicenter was located at 38.322°N, 142.369°E off the east coast of Honshu, Japan (Smith, 2011; <http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usc0001xgp/>). Displacements of the adjacent seabed generated gigantic tsunami waves damaging countless coastal communities around the Tohoku region. Tsunami heights up to 30 meters or more were observed in locations along the east coast of Honshu. Figure 1 shows the locations of the epicenter and the 5 (=4+1) ionosondes. Table 1 lists the ionosonde locations and the distances from the epicenter to the 5 ionosondes as well as the traveling times (i.e. the arrival time minus the earthquake onset time) of 3 different STIDs. Sequences of the ionograms are recorded with 15 and 5 minute resolutions by 4 Japan and 1 Taiwan ionosondes, respectively. After the earthquake onset at 05:46:23 UT, 3 out of the 4 Japan ionosondes recorded STIDs in their

Fig. 1. Locations of the Tohoku epicenter and 5 ionosondes at WAK (Wakkanai), KOK (Kokubunji), YAM (Yamagawa), OKI (Okinawa), and CHL (ChungLi). The epicenter and ionosondes are denoted by red star and blue triangles, respectively.

Table 1. Locations, distances to the epicenter and traveling times of the ionosonde. The distance is computed by the spherical coordinate with the Earth's radius of 6371 km.

Ionosonde	Distance (km)	d_{t1} (sec)	d_{t2} (sec)	d_{t3} (sec)
WAK (45.2°N, 141.8°E)	769	N/A	817	6217
KOK (35.7°N, 139.5°E)	387	N/A	817	N/A
YAM (31.2°N, 130.6°E)	1,334	N/A	2617	8017
OKI (26.7°N, 128.2°E)	1,850	817	2617	9817
CHL (25.0°N, 121.2°E)	2,482	1417	2917	11917

ionograms at 06:00 UT (the traveling time was 817 sec). OKI was the longest distance (1850 km) from the epicenter among the 4 ionosondes, and therefore the 1st STID propagation speed is at least 2300 m/s ($2.3 = 1850/817$ km/s) (Fig. 2 and Table 1). Assuming that the STID takes 4 minutes from the Earth's surface to an altitude of 200 km which is estimated from the ionograms by a true height analysis (Titheridge, 1985) of the ionosphere, we find that the speed could possibly be up to 3200 m/s ($3.2 = 1850/(817 - 240)$ km/s). On the other hand, the 1st STID detected at CHL was at 06:10 UT. Based on an epicenter distance of 2482 km and the traveling time of 1417 sec, the 1st STID propagation speed estimated at CHL is 1800 m/s ($1.8 = 2482/1417$ km/s) (Fig. 2 and Table 1). After removing the 4 minutes, the speed should be about 2100 m/s ($2.1 = 2482/(1177)$ km/s). Thus, the propagation speed of the 1st STID estimated from OKI and CHL is in the range 2100–3200 m/s (2.1–3.2 km/s). Since the 1st STID only appeared in ionograms recorded by two ionosondes, the circle method is not applicable.

An examination of the sequences of the ionograms shows that highly-fluctuated STIDs appear at WAK and KOK at 06:00 UT, YAM and OKI at 06:30 UT, and CHL at 06:35 UT. Since the STIDs are assumed to be detected at a fixed altitude of 200 km, we can simply consider their horizontal distances and speeds. For simplicity, we let the STID

onset time be 4 minutes late (i.e. 05:50 UT) at the ionospheric height of 200 km after the earthquake occurrence time 05:46:23 UT. In this case, the traveling times would be 4 minutes shorter than those listed in Table 1. Due to the sampling rate of every 15 minutes, an error of ± 7.5 minutes has been added into the traveling time. Note that the AGW propagation of 4 minutes from the Earth's surface to the 200 km altitude is smaller than the error of 7.5 minutes. Here, instead of circular lines (i.e. without considering the error), circular zones are plotted (the inner radius $R_i = (d_t - 7.5 \text{ min}) \times V_H$ and the outer radius $R_o = (d_t + 7.5 \text{ min}) \times V_H$, where d_t is the traveling time and V_H is the trying/testing speed). The traveling time listed in Table 1 minus 4 minutes. We apply the circle method by trying horizontal speeds of 600–1200 m/s with a step of 50 m/s. Figure 3 shows that with a horizontal speed of 900 m/s, 5 circular zones intersect at one location, which is right above the Tohoku epicenter.

Following the 1st and 2nd STID signatures, remarkably sinusoidal/wavy uplift STIDs appeared at WAK at 0730 UT, YAM at 08:00 UT, OKI at 08:30 UT and CHL at 0905 UT. Note that no clear feature can be found at KOK. Again, applying the circle method with horizontal speeds in the range 100–300 m/s with a step of 50 m/s, we find that for a horizontal speed of 200 m/s (or 720 km/hr), 4 circular zones intersect at one location, which is near the tsunami origin and/or the Tohoku epicenter.

3. Discussion and Conclusions

Many studies report STIDs triggered by the 11 March, 2011, M 9.0 Tohoku Earthquake by means of TEC (total electron content) derived from ground-based GPS receivers of GEONET (Maruyama *et al.*, 2011; Rolland *et al.*, 2011; Tsai *et al.*, 2011) and ionograms of ionosondes (Maruyama *et al.*, 2011). Three different STIDs are observed by the 5 ionosondes after the earthquake. The 1st STIDs with rather small disturbed amplitudes but very high propagation speeds of 2100–3200 m/s (2.1–3.2 km/s) which is in agreement with 3 km/s by Rolland *et al.* (2011) and 2.3 km/s by Tsai *et al.* (2011). The high speed waves might be induced by vertical motions of the solid Earth's surface of Rayleigh waves of the earthquake. Due to the high speed of 2–4 km/s and relatively short duration of several seconds/minutes, it requires some coincidence for ionosondes to observe STIDs triggered by the Rayleigh waves.

However, large vertical motions around the epicenter can generate acoustic (pressure) waves and gravity (buoyancy) waves (i.e. AGWs) in the neutral atmosphere, which can further propagate into the ionosphere and interact with the ionized gas. The highly-fluctuated features indicate these waves with various amplitudes, frequencies, and speeds confoundedly/concurrently reaching the ionosphere. The AGW speed is a function of the ratio of specific heat, temperature, molecular weight, wind speed, etc. For those traveling below the mesopause of 90 km altitude, the average AGW speeds are about 300–400 m/s (Liu *et al.*, 2006), while for those departing with relatively high elevation angles and mainly traveling in the ionosphere (or thermosphere) above 100 km altitude, the associated average AGW speeds could be up to 700–1100 m/s (cf. Artru *et al.*, 2004;

Fig. 2. The 1st STID arrived at OKI at 06:00 UT and CHL at 06:10 UT. Red arrows denote signatures of the STID.

Fig. 3. Ionograms with the 2nd STID recorded at the 5 ionosondes and the results of the circle method. Red arrows denote signatures of the STID.

Heki and Ping, 2005; Liu *et al.*, 2010). Therefore, the speed of 900 m/s suggests the 2nd STID being related to AGWs mainly traveling in the ionosphere of about 200 km altitude, which is close to the value of 1032–1045 m/s given by Liu *et al.* (2011) and the 1 km/s (1000 m/s) given by Rolland *et al.* (2011).

On the other hand, the sinusoidal traces in the ionograms of WAK, YAM, OKI, and CHL suggest that the triggering source has a relatively long period. A study of the 5-min time resolution ionograms shows that the period of the 3rd STID is in the range 15–20 minutes and the associated speed is 200 m/s (or 720 km/hr) which is close to 225 m/s

Fig. 4. Ionograms with the 3rd STID recorded at 4 of the 5 ionosondes and results of the circle method. Red arrows denote signatures of the STID.

by Rolland *et al.* (2011) and 210 m/s by Tsai *et al.* (2011). The agreements suggest that the 3rd STID is induced locally by the tsunami wave right under it.

For simplicity, we assume that the STIDs take 4 minutes traveling vertically from the Earth's surface to the ionosphere of 200 km altitude and examine the horizontal propagations of the origins of the STIDs accordingly. It is essential to find whether this assumption is reasonable and appropriate. Liu *et al.* (2011) report that STIDs of the GPS TEC first appear near the epicenter about 7 minutes after the Tohoku Earthquake onset, while Tsai *et al.* (2011) find that the STIDs in the GPS TEC triggered by the Rayleigh waves appear 7–8 minutes after the earthquake occurrence. Maruyama *et al.* (2011) further cross-compare concurrent/co-located GPS TECs and ionograms recorded by the 4 ionosondes in Japan during the Tohoku Earthquake. They find the earlier onset of the disturbance in the ionogram than the commencement of the propagating TEC perturbation. Since fluctuations in TEC are sensitive to the disturbance near the F_2 peak (about 350 km altitude), while the observed ionosonde STIDs are at the reflection height of about 200 km altitude, the 4-minute time lag should be reasonable for the STIDs directly and/or locally triggered

by Rayleigh and tsunami waves under them (i.e. the 1st and 3rd STIDs). However, it might take longer than 4 minutes for the internal AGWs, such as the 2nd STID. Nevertheless, due to the ionosonde sampling rate of every 15 minutes, the 4-minute assumption, or even slightly longer, is reasonable and appropriate.

In conclusion, the STIDs induced by the Rayleigh waves, ionospheric AGWs, and tsunami waves have been observed by ionograms recorded by the 5 ionosondes near the earthquake. The circle method can be used to locate origins and enable the determination of the propagation speed of STIDs triggered by seismic waves and tsunami waves of large earthquakes.

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Fig. A.1. Magnified Fig. 2 by zooming the sounding frequency (1–7 MHz) and virtual height (0–400 km).

Fig. A.2. Magnified Fig. 3 by zooming the sounding frequency (1–7 MHz) and virtual height (0–400 km).

Appendix A.

To clarify the influence of the different phenomena, the ionograms in Figs. 2, 3, and 4 have been magnified by zooming the sounding frequency (1–7 MHz) and the virtual height (0–400 km), respectively.

Fig. A.3. Magnified Fig. 4 by zooming the sounding frequency (1–7 MHz) and virtual height (0–400 km).

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