Ionospheric disturbances triggered by the 11 March 2011 M9.0 Tohoku earthquake

Jann-Yenq Liu,1,2,3 Chia-Hung Chen,4 Chien-Hung Lin,5 Ho-Fang Tsai,6 Chieh-Hung Chen,7 and Masashi Kamogawa8

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[1] An earthquake of magnitude 9.0 occurred near the east coast of Honshu (Tohoku area), Japan, producing overwhelming Earth surface motions and inducing devastating tsunamis, which then traveled into the ionosphere and significantly disturbed the electron density within it (hereafter referred to as seismotraveling ionospheric disturbances (STIDs)). The total electron content (TEC) derived from nationwide GPS receiving networks in Japan and Taiwan is employed to monitor STIDs triggered by seismic and tsunami waves of the Tohoku earthquake. The STIDs first appear as a disk-shaped TEC increase about 7 min after the earthquake occurrence centered at about 200 km east of the epicenter, near the west edge of the Japan Trench. Fast propagating disturbances related to Rayleigh waves quickly travel away from the epicenter along the main island of Japan with a speed of 2.3–3.3 km/s, accompanied by sequences of concentric circular TEC wavefronts and followed by circular ripples (close to a tsunami speed of about 720–800 km/h) that travel away from the STID center. These are the most remarkable STIDs ever observed where signatures of Rayleigh waves, tsunami waves, etc., simultaneously appear in the ionosphere.


1. Introduction

[2] During earthquakes, vertical motions of the Earth’s surface create mechanical disturbances (waves) and trigger the acoustic gravity waves (AGWs) in the neutral atmosphere, which propagate into the ionosphere and interact with the ionized gas (hereafter referred to as seismotraveling ionospheric disturbances (STIDs)) [Davies, 1990]. Using ionosondes recorded by MF/HF (median/high-frequency) ionosondes and frequency shifts probed by HF Doppler sounders, scientists have observed STIDs triggered by strong earthquakes [Bolt, 1964; Leonard and Barnes, 1965; Davies and Baker, 1965; Row, 1967; Yuen et al., 1969; Tanaka et al., 1984; Artru et al., 2004; Liu et al., 2006a]. However, due to limited numbers and/or coverage of ionosonde or Doppler sounding networks, it has been rather difficult to study STID propagation in detail. To simultaneously monitor a large area of the ionosphere, a network of ground-based receivers of the global positioning system (GPS) is ideal to be used. Scientists apply the GPS technique to observe STIDs of the total electron content (TEC) triggered by seismic waves [Calais and Minster, 1995; Ducic et al., 2003; Afraimovich et al., 2001; Heki and Ping, 2005; Liu et al., 2010] or by tsunami waves [Otsuka et al., 2006; Artru et al., 2005; Liu et al., 2006b].

[3] The U.S. Geological Survey reports that the origin time of an M9.0 earthquake was at 05:46:23 UT (universal time); while the epicenter was located at 38.322°N, 142.369°E near Miyagi city, off the east coast of Honshu, Tohoku area, Japan (http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/us0001xgpy/). Displacement of the adjacent seabed generated gigantic tsunami waves damaging countless coastal communities around the Tohoku area. Maximum tsunami heights of as much as 30 m were observed in locations along the east coast of Honshu. The earthquake occurred near two dense networks of ground-based GPS receivers in Japan and Taiwan, which allows us to pinpoint the origin and evolution of various STIDs triggered by the Tohoku earthquake and its associated tsunami on 11 March 2011. In this paper, the TEC derived from the two densest GPS networks is used to observe the STIDs triggered by the M9.0 Tohoku earthquake.

2. Observation

[4] Signatures of the devastating seismic surface and tsunami waves of the Tohoku earthquake in the ionosphere were observed by means of ground-based GPS receiver networks of the GPS Earth Observation NETwork (GEONET) in Japan...
Figure 1. Seismic surface waves around the epicenter (red star) vertically launch atmospheric gravity waves that propagate into the ionosphere. The slant TEC (dashed line) is the integration of electron density from a ground-based receiver to a GPS satellite. The vertical component of the slant TEC at the intercept (or ionospheric point) of the slant path on the ionospheric surface is termed a vertical TEC (solid line). The footprint of the seismoionospheric point on the Earth is termed the subionospheric point. Each ionospheric point acts as a space seismometer to detect STIDs.

and of the TaiWan Network (TWN) in Taiwan. Figure 1 shows a diagram illustrating that vertical motions of seismic surface waves induce atmospheric AGWs, which then travel into the ionosphere and disturb the electron density or TEC within it (i.e., STIDs). Assuming the ionosphere to be a thin spherical shell at a height of 350 km, the intercept of the slant path of GPS signals on the ionospheric shell surface can serve as a space seismometer (or tide gage) floating at an ionospheric point at 350 km altitude for monitoring STIDs (Figure 2). When STIDs pass through the slant paths between GPS satellites and ground-based receivers, they can be detected by the slant TEC anomalous changes of the associated space seismometers and/or tide gages. GEONET and TWN consist of nearly a thousand and more than a hundred of ground-based GPS receivers, respectively (Figure 2). Up to 11 GPS satellites were observed by each of 1098 stations in these dense receiver networks around the earthquake, this is equivalent to having more than 12000 (1098 total stations multiplied by 11 GPS satellites) space seismometers and/or tide gages being employed to monitor the STIDs triggered by the Tohoku earthquake with sampling rate of 30 s. Figure 3 reveals time evolutions of the band-pass filtered GPS-TEC, which shows that the STIDs begin as a disk-shaped TEC increase with the radius of about 200–300 km centered at 200 km east from the epicenter at 05:53–05:55 UT (supplementary Movies S1, S2, and S3).1 While the TEC increase further enhances and expands, a ring-shaped TEC decrease appears northeast of the enhanced area at 06:00 UT. Following that, the peaks and troughs of concentric circular wavefronts start propagating radially away from the STID center/origin, and short-wavelength waves quickly travel away from the epicenter along the main island of Japan in both the northeast and southwest directions at 06:06 UT. The southwest propagating short wave first arrives in Taiwan at 06:10 UT. The distance between Taiwan and the epicenter is about 2500 km. If it is assumed that all the STIDs are simultaneously induced on the Earth’s surface and reach the ionosphere at about 05:53 UT, the short wave speed is 2.45 (~2500 km/17 min) km/s, which generally agrees with the Rayleigh wave speed. The short waves eventually disappear, the concentric circular wavefronts become prominent after 06:25 UT, and later circular ripples with slower speed turn into dominant before gradually diminishing by 08:00 UT. The origin of STIDs located right above the sea trench (Figure 2) suggests that the circular wavefronts and ripples are triggered by the tsunami.

[5] To further understand the propagation of the STIDs, the observed TEC disturbances are plotted as a function of the distance to the epicenter versus the time after the earthquake occurrence, for the 4 GPS satellites (PRN 09, 15, 18, and 27) near mainland Japan. Similar approach was reached by earlier studies [cf. Ducic et al., 2003; Heki and Ping, 2005; Liu et al., 2010]. Figure 4 illustrates various propagation speeds that can be roughly divided into two groups. In one group, fast speeds of a few kilometers per second are observed, while the other group consists of slow speeds at hundreds of kilometers per hour (about 200 m per second). The STIDs with 2.3–3.3 km/s (2285.57–3303.31 m/s) and 720–800 km/h (202.68–220.37 m/s) are related to the Rayleigh waves [Calais and Minster, 1995; Ducic et al., 2003] and tsunami [Artru et al., 2005; Liu et al., 2006b; Otsuka et al., 2006], respectively. On the other hand, various STIDs appear between the two groups with speeds of 600–1500 m/s and 290–310 m/s. Nevertheless, the speed and amplitude of the STIDs become slower and smaller as the time goes by.

3. Discussion and Conclusion

[6] In previous studies, observed STID signatures were usually induced by a single source: either Rayleigh waves [Calais and Minster, 1995; Ducic et al., 2003], seismo-AGWs in the ionosphere [Afraimovich et al., 2001; Heki and Ping, 2005; Otsuka et al., 2006; Liu et al., 2010], or tsunami

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1Auxiliary materials are available in the HTML. doi:10.1029/2011JA016761.
Disturbances were observed individually. Due to the powerful M9.0 Tohoku earthquake occurring near the two densest ground-based GPS networks in the world, numerous AGWs, including signatures of Rayleigh, tsunami waves, etc., appear simultaneously. It is found that the STIDs reaching the ionosphere in about 7 min after the earthquake occurs. Since the ionosphere is assumed to be a thin spherical shell at a height of 350 km, the average speed of the STID traveling from the Earth’s surface to the ionosphere is about $833 = \frac{350 \text{ km}}{7 \text{ min} / 60 \text{ s}}$ m/s, which agrees with those observed by Liu et al. [2006a, 2006b]. Meanwhile, the observed speeds of 2.3–3.3 km/s and 720–800 km/h are nearly identical to the speeds of Rayleigh waves and tsunami waves, which suggest that the two STIDs are locally induced by the two waves right under them [Liu et al., 2006a, 2006b]. It has been known that vertical motions of the solid surface near the epicenter and/or the sea surface around the tsunami origin trigger disturbances (i.e., acoustic gravity waves) in the neutral atmosphere. Artru et al. [2004] and Heki and Ping [2005] show that the acoustic speed is about 300 m/s from the Earth’s surface to the mesosphere at about 90–100 km altitude, and speed up to 1000–1100 m/s at 300 km altitude in the ionosphere. Therefore, if the triggered disturbances (i.e., AGWs) depart with low elevation angles, they travel near horizontally between the troposphere and the mesosphere with speeds of about 300 m/s, and further locally/vertically perturb the ionospheric TEC (i.e., STID) [Liu et al., 2006a]. On the other hand, those AGWs depart with high elevation angles, travel near vertically into the thermosphere (ionosphere), and propagate horizontally interacting with the ionized gas. Thus, due to the AGWs (i.e., STIDs) traveling most of the time in the ionosphere, the speeds are of 600–1100 m/s [Afraimovich et al., 2001; Heki and Ping, 2005; Otsuka et al., 2006; Liu et al., 2010]. For those speeds greater than 1100 m/s, such as 1596.67 m/s (Satellite 15 in Figure 4), they might result in...

**Figure 3.** Band-pass filtering of the total electron contents derived from GPS observations at studied times. The TEC disturbances extracted from the filtering with periods of 120–350 s are plotted at their sub-ionospheric point. The Rayleigh wave signature is seen prior to 06:11 UT propagating from mainland Japan to Taiwan. The origin of the concentric circular wavefronts and ripples appears near the west edge of the Japan Trench.
from mode mixings of the STIDs induced by Rayleigh waves and acoustic waves near the epicenter right after the earthquake occurrence [Astaev et al., 2009].

It was reported that STIDs propagations had strong north-south asymmetry. Scientists hypothesized that the northward propagating disturbances might be selectively attenuated by interaction between the movements of charged particles in STIDs and the Earth’s magnetic fields [Heki and Ping, 2005; Otsuka et al., 2006]. For the event studied here, signatures of the Rayleigh waves travel away from the epicenter along the Japanese island in both the northeast and southwest directions with speeds of 2.1–3.0 km/s, while those of acoustic and tsunami waves propagate in all directions. The Tohoku earthquake is the 5th largest earthquake after 1900. The massive energy released by this event has an immense impact extending from the surface of the Earth up into the ionosphere, as observed by the two densest ground-based GPS networks of the world. The resulting data set illustrates the dynamics and physical mechanisms of ionospheric disturbances/waves triggered by the M9.0 Tohoku earthquake in unprecedented detail.

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References


C.-H. Chen, Department of Geophysics, Kyoto University, Kyoto 606-8502, Japan.


M. Kamogawa, Department of Physics, Tokyo Gakugei University, Tokyo 184-8501, Japan.

C.-H. Lin, Department of Earth Science, National Cheng Kung University, Tainan 701, Taiwan.

J.-Y. Liu, Institute of Space Science, National Central University, Chung-Li 32001, Taiwan. (jyliu@jupiter.ss.ncu.edu.tw)

H.-F. Tsai, Central Weather Bureau, 64 Gongyuan Rd., Taipei 110048, Taiwan.