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Seismo-Geomagnetic Pulsations Triggered by Rayleigh Waves of the 11 March 2011 M 9.0 Tohoku-Oki Earthquake

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ABSTRACT

This study reports on geomagnetic pulsations excited by traveling Rayleigh waves. The geomagnetic total intensity fields recorded using 12 magnetometers are utilized to examine seismo-magnetic pulsations induced by the 2011 M 9.0 Tohoku-oki earthquake. Geomagnetic data and seismograms from 4 co-located seismometers are examined and cross-compared to determine whether magnetic variations result changes in space weather or traveling Rayleigh waves. A 150 - 250 s band-pass filter was adopted to determine the arrival times and amplitudes of the seismo-magnetic pulsations. Seismo-magnetic pulsations with pronounced periods of about 200 s and amplitudes of 0.2 - 1.2 nT appear at distances ranging from 190 - 4600 km from the epicenter. Pulse speed of 3.8 km s^{-1} estimated from the epicentral distances and arrival times indicates that the seismo-magnetic pulsations were induced by Rayleigh waves produced by the Tohoku-oki earthquake. The seismo-magnetic pulsations constantly lag seismic wave pulses by about 6.3 minutes, confirming that ionospheric conductivity affects magnetic fields.

Key word: Tohoku-oki earthquake, Rayleigh wave, Magnetic pulsations

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1. INTRODUCTION

At 05:46:23 UT (universal time), 11 March 2011, a destructive M 9.0 earthquake (142.86°E, 38.10°N) occurred off the east coast of the Tohoku-oki region of Honshu, Japan. This earthquake was subsequently dubbed the Tohoku-oki earthquake by scientists (Hirose et al. 2011). The Centroid Moment Tensor analysis of the main shock indicates that the Tohoku-oki earthquake is the reverse fault type with strike 203°, dip 10°, and rake 88° (also see Fig. 1; http://www.globalcmt.org/). The significant co-seismic crustal displacements associated with the 2011 Tohoku-oki earthquake were observed mainly at the eastern part of Japan (i.e., > ~139°E) and reported in many previous studies (Nishimura et al. 2011; Ozawa et al. 2011; Simons et al. 2011; Lee 2012; Wei et al. 2012). Fujii et al. (2011) used 33 coastal tide gauges, offshore GPS wave gauges and bottom-pressure gauges to identify a large slip, more than 40 m along the trench axis. Great fault slips trigger intense seismic waves and dislocate the adjacent seabed, resulting in gigantic tsunami waves with heights as great as 1.9 m in the deep ocean (Simons et al. 2011) and about 5 - 35 m near the Japan coastal region (Maeda et al. 2011; Mori et al. 2011; Goto et al. 2012; Lin et al. 2012). The Tohoku-oki earthquake killed more than 10000 people (Fujii et al. 2011). The intense co-seismic changes and gigantic tsunami caused maximum variations of 0.8 nT near the epicenter and rapid changes during the hours following the main shock in the geomagnetic field (Utada et al. 2011). Intense variations in the ionosphere excited by Rayleigh waves and/or Tohoku-oki earthquake tsunamis were found through the total electron content (TEC) from dense GPS networks (Liu et al. 2011; Tsugawa et al. 2011; Huang et al. 2012; Kamogawa et al. 2012).

Magnetic pulsations can be directly excited by either radiated seismic waves (e.g., Breiner 1964; Eleman 1965; Iyemori et al. 1996; Tsegmed et al. 2000; Yamazaki 2012) or sudden vertical motion by the ocean floor (Iyemori et al. 2005). Honkura et al. (2004) proposed that magnetic pulsations in either electric or magnetic fields could be triggered

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by P wave (i.e., primary or pressure wave) arrivals. Ujihara et al. (2004) examined the effects by comparing measurements from induction coils buried under the ground and hanging in the air. They observed that seismo-magnetic pulsations were instantly generated from induction coils buried in the ground. Yamazaki (2012) quantified the changes in geomagnetic field raised by Rayleigh waves located a significant distance from earthquake epicenters through Maxwell's equations. Magnetic pulsations directly induced from seismic waves can be observed in a wide frequency band from VLF to ULF using either 3-component magnetometers or magnetotelluric equipment within an epicentral distance of ~500 km. These pulsations are usually very tiny (~10^{-1} nT) and close in amplitude to the background noise (Johnston et al. 1981; Guglielmi et al. 2004). Guglielmi et al. (2004) used a polarization method against a noise background and recognized the seismo-magnetic pulsations accompanying Love waves propagated from a M 7.9 earthquake on 18 June 2000. Iyemori et al. (2005) reported that magnetic pulsations with periods of about 30 and 216 s could be generated using an atmospheric pressure pulse due to sudden vertical motions of the ocean floor shortly after the 26 December 2004 M 9.3 Sumatra-Andaman earthquake.

This research examines magnetic pulsations associated with variations in the ionospheric plasma density triggered by Rayleigh waves. A geomagnetic network of 12 stations equipped with continuous recording systems (GSM90F with 0.01 nT resolution) was constructed to monitor the changes in geomagnetic field in Taiwan (Yen et al. 2004, 2009; Chen et al. 2009). The geomagnetic total intensity fields are computed and further utilized for comparison in this study. Geomagnetic total intensity field measurements with 1 Hz resolution at 12 stations: 1 in Taiwan (a reference station in Taiwan's network), 4 in Japan, 3 in China, 3 in Australia, and 1 in French Polynesia (see Fig. 1), were utilized to survey magnetic pulsations possibly triggered by the Tohoku-oki earthquake seismic waves. The pulse velocities derived from magnetic pulsation arrival times versus the epicentral distance are compared with multiple seismic waves using seismograms recorded at 8 stations. Measurements from 4 co-located seismometers and magnetometers were employed to determine the time delay between seismic waves and the associated magnetic pulsations. The Fourier transform was further applied to find the frequency and amplitude of the triggered magnetic pulsations. The consistent lead times observed at various locations and distinct epicentral distances allow us to have a better understanding of the possible magnetic pulsation causal mechanisms.

2. OBSERVED DATA

When magnetic total intensity data recorded by 12 magnetometers during the Tohoku-oki earthquake are concerned, two pronounced magnetic pulsations are observed: one with a long period of about 200 s and an amplitude of 0.2 - 1.2 nT during 400 - 2200 s, and the other with a short period of about 40 s and an amplitude of < 1 nT at most stations during 1800 - 2200 s after the earthquake. The short period pulsations are synchronized and appear simultaneously at the 12 magnetic stations, suggesting that they are space weather related. By contrast, the occurrence (or arrival) times of the long period pulsations are proportional to the distances from the epicenter to the magnetic stations. Note that a similar relation can be found in the seismic wave

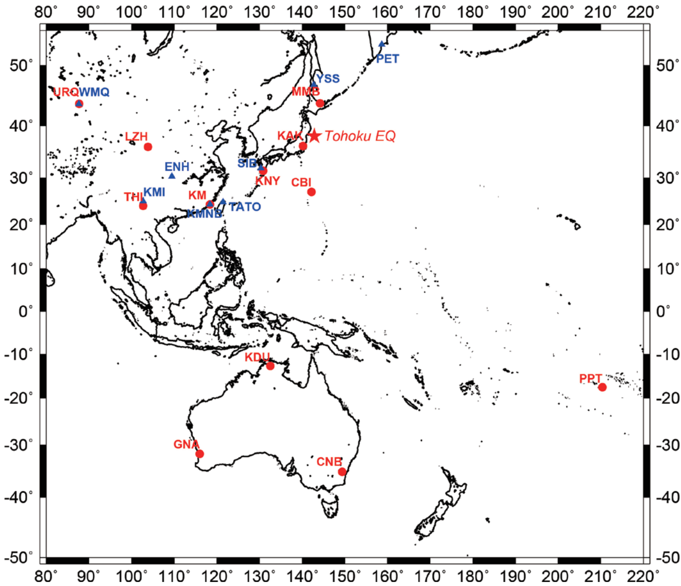

Fig. 1. Location of the magnetic stations, seismometers and the epicenter of the Tohoku-oki earthquake. Solid circles, blue solid triangles, and the star denote magnetic stations, seismometers and the epicenter of the Tohoku-oki earthquake, respectively.

arrival times recorded by the 4 seismometers and their distances from the epicenter.

The Fourier transform is applied further to reveal and/or separate long period and short period magnetic pulsations in detail. Figure 2a reveals that the long period pulsation amplitudes deduced using a band-pass filter 150 - 250 s in period are inversely proportional to the epicentral distance. The magnetic pulsation and epicentral distance indicate a speed of 3.8 km s^{-1}. Note that the enhanced amplitude and background noise are comparable at the 4 furthest stations. By contrast, Fig. 2b shows that the short period pulsation amplitudes deduced using a band-pass filter 20 - 60 s in period appeared simultaneously regardless of the epicentral distance. The largest short period pulsation enhanced amplitude is observed at the PPT station far away from the Tohoku-oki earthquake. The short period pulsations are thus referred to as magnetic storm (Utada et al. 2011). A band-pass filter 150 - 250 s in period was applied to seismograms recorded by 8 seismometers (Fig. 3). Filtered Rayleigh waves from the Tohoku-oki earthquake have a traveling speed of 3.8 km s^{-1}. The filtered seismo-magnetic pulsations are generally observed following the arrival of the filtered seismograms with a delay of about 6.3 minutes. Variations in filtered seismo-magnetic pulsations and seismograms are consistent when the filtered seismograms are shifted with necessary modification in the time scale.

3. DISCUSSION

Previous theoretical and observational works reported that Rayleigh wave propagation induces acoustic waves in the atmosphere and ionosphere by dynamic coupling (Lognonné et al. 1998; Artru et al. 2004; Liu et al. 2006, 2010; Occhipinti et al. 2010). Gravity waves generated by tsunami propagation also (and strongly) perturb the ionosphere (Rolland et al. 2010) and the direct acoustic wave from the epicenter (Heki et al. 2006). Since the speeds of Rayleigh waves, internal gravity waves and direct acoustic waves range mainly from 3 - 4, 0.3 - 0.5, and 0.8 - 1.0 km s^{-1} (Heki et al. 2006; Liu et al. 2011), respectively, seismo-magnetic pulsations with a horizontal speed of about 3.8 km s^{-1} reported in this study are related to neither the internal gravity wave nor the direct acoustic wave activated by the Tohoku-oki earthquake. Guglielmi et al. (2004) and Honkura et al. (2004) showed that the P and/or Love wave can trigger seismo-magnetic pulsations without a noticeable time delay. The propagation speeds of P and Love/Rayleigh waves are generally 5 - 6 and 2 - 4 km s^{-1} (Shearer 1999), respectively. Based on the relationship between the epicentral distances and occurrence times shown in Figs. 2 and 4, the magnetic pulsations

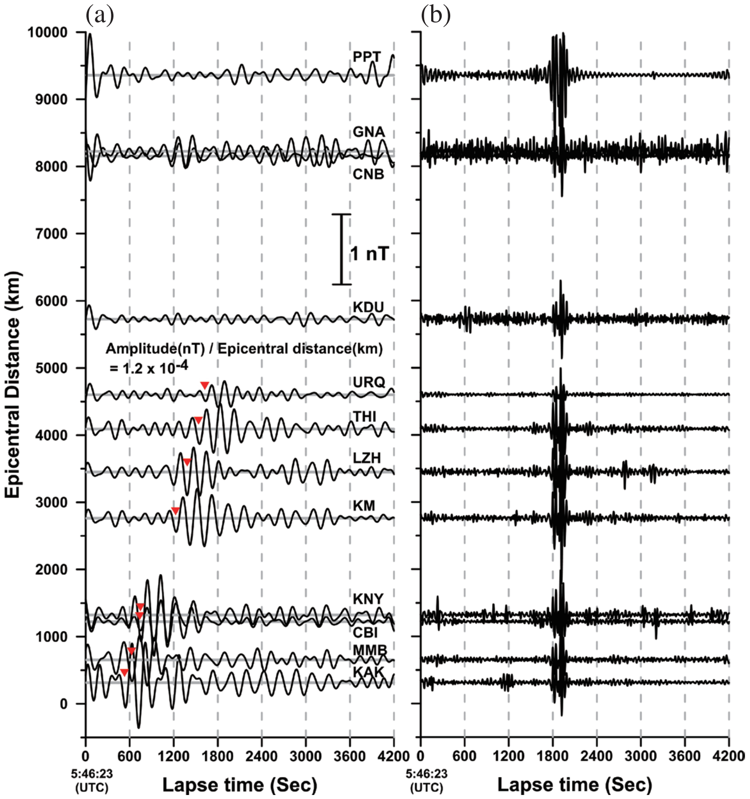

Fig. 2. Variations in magnetic pulsations at the 12 stations during the Tohoku-oki earthquake. The origin time is the occurrence of Tohoku-oki earthquake. The left (right) panel shows variations of the long (short) period magnetic pulsations deduced using a band-pass filter of 150 - 250 (20 - 60) s in period via the Fourier transform. The triangle denotes the first visible energy of long period (seismo-) magnetic pulsations.

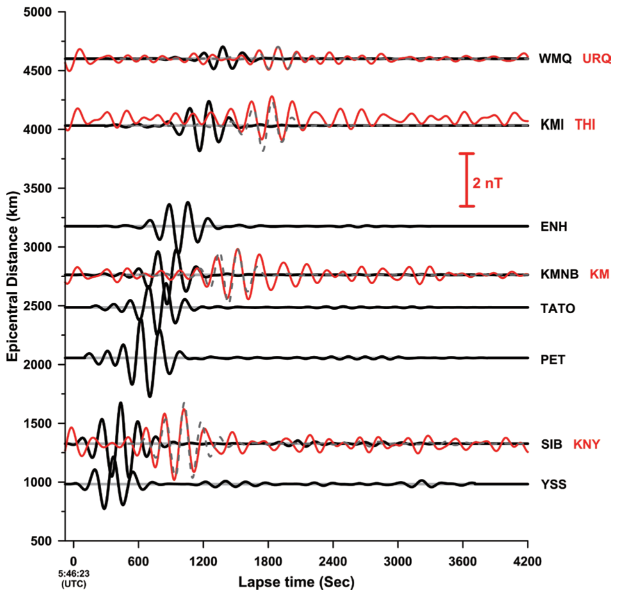

Fig. 3. Comparison between the filtered seismograms and seismo-magnetic pulsations using a band-pass filter of 150 - 250 (20 - 60) s in period via the Fourier transform. The origin time is the occurrence of Tohoku-oki earthquake. The black lines denote the filtered seismograms recorded by 8 seismometers. The red lines show the filtered seismo-magnetic pulsations at 4 co-located magnetic stations. Note that the black dashed lines are the filtered seismograms shifted with necessary modification in the time scale. The scale and unit is in "counter" which vary seismometer by seismometer.

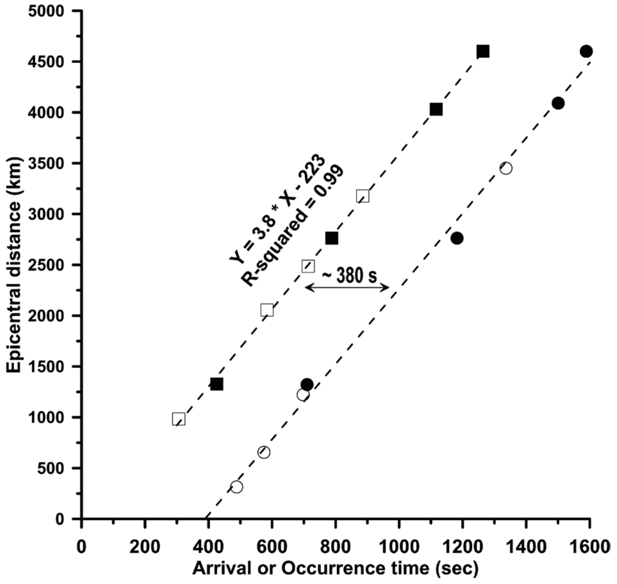

Fig. 4. Relationships between the epicentral distance and arrival (occurrence) times of Rayleigh waves (the magnetic pulsations). The black squares (circles) with the dashed line as a fitting curve are retrieved from seismograms (magnetic data). The solid symbols show the co-located stations for comparison. Note that the error bar in the time scale is given by the difference from the first visible to the maximum energies in the filtered data.

with a speed of about 3.8 $\mathrm{km\ s^{-1}}$ observed in this study are not related to the P waves from the Tohoku-oki earthquake. It has been known that Rayleigh and Love waves yield pronounced vertical and horizontal motions on the Earth's surface, respectively. Based on the efficiency in triggering seismo-AGWs (acoustic gravity waves), the magnetic pulsations are induced by Rayleigh waves, which result mainly in the Earth's surface vertical motion. Figure 4 shows that appearance of the long period magnetic pulsations with about 4-minute time delay follow the arrival of Rayleigh waves. This suggests that the long period pulsations are not directly/instantly excited by the ground motion due to the arrival of Rayleigh waves but induced by variations in the ionospheric plasma density triggered by Rayleigh waves via AGWs (acoustic waves, AWs in Rolland et al. 2011).

Francis (1973) reported that seismo-geomagnetic pulsations with long periods (> 240 s) could be caused by atmospheric pressure oscillation at altitudes of about 110 km due to a duct resonance of AGWs between the ground and lower ionosphere. Iyemori et al. (2005) report that the time lag of 12 minutes is consistent with the time necessary for an AGW to travel from the ground to the ionospheric E-region (about 6 minutes, or 360 s) and reflect back to form a duct resonance. Although the pulsation period of about 200 s observed in this paper is somewhat similar to those reported in previous studies, the seismo-magnetic pulsations constantly lag the seismic waves by about 6.3 minutes, which is very different from the time lag of 12 minutes reported by Iyemori et al. (2005). Therefore, the seismo-magnetic pulsations observed in this paper are unlikely to be related to duct resonance.

Liu et al. (2012) showed that sudden vertical motions on the Earth's surface from the Rayleigh wave can efficiently create/induce mechanical disturbances in the atmosphere (i.e., seismo-AGWs) near the Earth's surface. Davies (1990) showed that seismo-AGWs near the Earth's surface can propagate into the ionosphere and interact with the ionized gas. The conductivities in the ionosphere are functions of the electron density, collision frequency, etc. In middle latitudes, the Hall and Pedersen conductivities reach their peaks at about 110 km altitude in the ionospheric E-region (Kelley 2009). Therefore, transit seismo-AGWs can easily disturb the collision frequency, the conductivities and modify the associated currents in the E-region, which in turn instantly change and/or affect (with the speed of light) the magnetic fields on the Earth's surface.

Liu and Sun (2011) examined ionograms recorded by 3 Japanese ionosondes near the Tohoku-oki epicenter and found that the travel time of STIDs (Liu et al. 2011) induced by the seismo-AGWs from the ground to the lower ionosphere is about 240 s. The time delay of about 6.3 minutes in this study is close to the travel time of 4 minutes reported by Liu and Sun (2011). In fact, these are both close to the 6 minutes necessary for an acoustic wave to travel from the ground to the ionosphere (Iyemori et al. 2005). These agreements suggest that the long period magnetic pulsations most likely result from seismo-AGWs triggered by Rayleigh waves near the Earth's surface, which then propagate upwards into the ionosphere, thus modifying the conductivities and currents within it.

4. CONCLUSION

Seismo-magnetic pulsations lag the seismograph in time by about 6.3 minutes, with the dominant period about 200 s and the seismo-magnetic pulsations triggered by seismo-AGWs locally generated by traveling Rayleigh waves 3.8 km s^{-1} below, which are unlikely related to direct acoustic waves from the epicenter. The traveling Rayleigh waves lift up or depress the Earth's surface, modulate atmospheric pressure near the ground and excite acoustic waves which propagate upwards into the ionosphere where they disturb the ionospheric E-region conductivities and currents producing seismo-magnetic pulsations with a time lag of about 380 s (6.3 minutes). Due to the current induction the seismo-magnetic pulsations will be simultaneously/instantly detected by a magnetometer located below.

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