Pure Appl. Geophys. 179 (2022), 4163–4178

https://doi.org/10.1007/s00024-021-02919-4

Pure and Applied Geophysics

Ahead-of-Tsunami Magnetic Disturbance Detection Using Intrinsic Mode Functions: Tohoku-Oki Earthquake Case Study

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Abstract—We document magnetic disturbances that occurred during the Tohoku-Oki tsunami of 11 March 2011 using empirical mode decomposition (EMD) in a dataset derived from a network of ground-based magnetometers (INTERMAGNET and GIS). The disturbances, obtained by filtering the magnetic field data using the first intrinsic mode function (IMF1) of EMD, propagate ahead of the tsunami at a speed in the range of 600–1.6 km/s. They also appear 3 min (near-field) to 2 h (far-field) earlier than the tsunami arrival at the magnetic observatories. We refer to these disturbances as ahead-of-tsunami magnetic disturbances (ATMDs). A comparison with seismometer data shows them arriving $\sim$10 min after the arrival of Rayleigh waves. Their association with both seismogenic and tsunamigenic processes is discussed, and it is argued that the tsunamigenic process can well explain the magnetic disturbance propagation characteristics at the far-field. At near-field, the ATMDs are the coseismic magnetic signatures mainly driven by surface Rayleigh waves. Monitoring these ATMDs can be extremely useful for the early warning of the tsunami.

Keywords: Tsunami, geomagnetism, AGWs, intrinsic mode function, Hilbert-Huang transform, signal processing.

1. Introduction

Several authors have shown the presence of ionospheric disturbances during earthquakes and/or tsunamis following an earthquake or landslide (Artru et al. 2005; Occhipinti et al. 2008; Astafyeva et al. 2009; Rolland et al. 2010, 2011; Savastano et al. 2017; Rakoto et al. 2018; Liu et al. 2020; Manta et al. 2020; Zhang et al. 2021). These disturbances are observed in the total electron content (TEC), measured from the Global Navigation Satellite System (GNSS), and in the geomagnetic field measured from ground-based magnetometer networks (Balasis and Mandea 2007; Manoj et al. 2011; Utada et al. 2011; Hao et al. 2013; Klausner et al. 2014, 2016a, b; Tatehata et al. 2015). All these research studies observed an N-shaped response of the ionosphere and the geomagnetic field upon the shock-like atmospheric waves excited by coseismic vertical movements of the ground or the sea surface. These disturbances are referred to as co-tsunami ionospheric disturbances (CTIDs). For example, in a tsunami with a 20-min period propagating at $\sim$200 m/s, the group velocity of a gravity wave in the thermosphere is $\sim$200 m/s (horizontal) and $\sim$40 m/s (vertical) (Artru et al. 2005). This means that the ionospheric disturbances have the same horizontal velocity as the tsunami. This horizontal velocity of tsunamigenic gravity waves is significantly lower than the acoustic gravity waves induced by an earthquake (horizontal velocities of $\sim$1000 m/s at the thermosphere) (Galvan et al. 2012). On the other hand, the gravity waves take over 1 h to reach the ionosphere (versus $\sim$10 min for shock-acoustic waves) (Astafyeva et al. 2009, 2011). After this delay, the ionospheric disturbances follow the tsunami front wave (Artru et al. 2005). There are a variety of wavefronts associated with the tsunami that were observed in the form of CTIDs (Kherani et al. 2016), which propagate horizontally in the thermosphere with acoustic wave speed of $\sim$600–1000 m/s, gravity wave speed of $\sim$250 m/s, and slower speed $\sim$200 m/s than the tsunami.

After an earthquake onset, seismic waves generate vertical and horizontal motion of the ground surface. Both acoustic and gravity waves can be launched by a seismic event. In addition, surface vertical

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00024-021-02919-4.

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