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NOTES AND CORRESPONDENCE

Common Observations for Near-Source Ground Motions and Seismo-Traveling Ionosphere Disturbances Following the 2011 off the Pacific Coast of Tohoku Earthquake, Japan

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ABSTRACT

The time history and spatial dependence of seismic-wave propagation on the ground surface and through the ionosphere following the 2011 off the Pacific coast of Tohoku Earthquake were reconstructed from dense seismic networks and from Global Positioning System (GPS) array observations, respectively. Using total electron content (TEC) data recorded by a dense GPS receiver network, the near-source ionosphere perturbations induced by this giant earthquake were analyzed and high-resolution images of seismic-wave propagation in the ionosphere are presented. Similar spatial images of ground motions were reconstructed from observations by a dense seismic array. Observations of this event provide, for the first time, the opportunity to compare near-source ground motions with the near-field seismo-traveling ionosphere disturbance (STID) excited by the ground motions. Based on the results, the nature of the source rupture and seismic-wave propagation are discussed. Both seismic and ionosphere observations indicate that seismic energy propagated radially outward initially from the hypocenter, but that the circular shape of the propagation front became gradually distorted as the source rupture became extended. Coherent wavefronts from the two analyses show contrasting patterns during the later stage of propagation, possibly due to different patterns of spatial variations in the physical properties of the solid earth and of the ionosphere.

Key words: Source rupture, GPS, TEC, STID

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1. INTRODUCTION

An important task in many research fields of seismology is to accurately constrain the kinematics of an earthquake rupture. Earthquake source inversions have become an almost routinely applied method for imaging the earthquake rupture process using seismic data (Kikuchi et al. 2000; Ji et al. 2002). However, in many cases the limitations of the available data mean that the source models for a given earthquake, as imaged by different research teams, are inconsistent with each other (Mai et al. 2007). Consequently, it is important to explore independent datasets to constrain the kinematics of earthquake ruptures.

Over the past two decades, geodetic observations from the Global Positioning System (GPS) have been employed to constrain the rupture geometry and to map the static displacement on fault planes. GPS data have also been used to observe the seismo-traveling ionosphere disturbances (STID) that occur after large earthquakes, enabling the detection of short-term anomalies in the total electron content (TEC) (Calais and Minster 1995; Ducic et al. 2003; Heki and Ping 2005; Liu et al. 2006, 2011). These signals may originate from near-field acoustic waves, far-field Rayleigh waves, or trans-oceanic or tsunami waves generated by earthquakes. For such waves, the ionosphere acts as a natural amplifier of ground measurements; the vertical velocity at ground level is amplified by a factor of up to 10^5 when it reaches the ionosphere (Lognonné et al. 2006).

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Depending on the excitation mechanism of the ionosphere by the earth's surface vibration, it is possible to overcome the geographic limitations of land-based seismic observations, to observe long period water waves in oceanic areas, and to extend the data coverage of seismic observations to resolve the source rupture process and to detect the occurrence of tsunami waves. Recently, the near-field STID has been employed to investigate the source and wave-propagation behavior of large earthquakes that occurred beneath the ocean (Heki et al. 2006; Astafyeva and Heki 2009; Liu et al. 2010, 2011).

To date, no dense array observations of STID have been obtained in the vicinity of an earthquake for the purpose of a detailed source analysis. However, the ionosphere disturbances recorded following the 2011 off the Pacific coast of Tohoku Earthquake, Japan, are encouraging in this regard because the propagation of seismic waves in the ionosphere was recorded with high spatial density, enabling the reconstruction of the two-dimensional (2-D) wavefield, which would be of use for various seismological studies. This study reports on the successful observation of seismic wavefields, in the crust and in the ionosphere, related to the 2011 event, and discusses the implications of this type of data for a detailed source analysis.

2. DATA

At 14:46 Japan Standard Time (05:46 Coordinated Universal Time) on 11 March 2011, the 2011 off the Pacific coast of Tohoku Earthquake (magnitude 9.0) was caused by a undersea megathrust event off the Pacific coast of Tohoku, Japan, with the hypocenter at a depth of approximately 24 km (Fig. 1). This event resulted from thrust faulting on or near the subduction zone plate boundary between the Pacific and North American plates. Strong ground motions and an anomalously large tsunami resulted in severe damage and more than 15000 fatalities over a wide region of Japan, particularly along the Pacific coast.

This study examines both seismic ground motions and ionospheric disturbances with the aim of constructing 2-D images of seismic-wave propagation. Surface ground motions were reconstructed using data recorded by seismic stations of the Kyoshin Network (K-NET) (Kinoshita 1998) and the Kiban Kyoshin Network (KiK-net) (Aoi et al. 2000), as well as a high-sensitivity seismograph network (Hi-net) (Obara 2002) of the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan. K-net and KiK-net are dense networks of strong-motion seismometers, and the Hi-net is a network of downhole short-period seismographs. These seismic arrays cover all of Japan and provide high-quality and uniform instrumental seismic records. In Japan, the GPS Earth Observation Network (GEONET) has been in operation for over a decade, with more than 1000 continuous receiving stations recording data on crustal deformation. Earthquake-excited STIDs recorded by this dense array have been employed to determine the apparent propagation velocity, directionality, waveform, and initial motion of seismic-wave propagation in the Earth's upper atmosphere (Heki and Ping 2005).

During the 2011 off the Pacific coast of Tohoku Earthquake, 381 K-net/KiK-net stations in the northern Honshu area recorded strong motions (Fig. 1). In this study, we analyzed vertical-component seismograms (with a sampling interval of 0.01 s) from these stations to reconstruct 2-D ground motions near the source area. Furthermore, more than 700 vertical velocity seismograms (with a sampling interval of 0.01 s) from Hi-net were used to reconstruct 2-D ground motions in areas where the K-net/KiK-net instruments were not triggered (Fig. 1). We also collected 2 hours of continuous data (with a sampling interval of 30 s) from 1228 GPS GEONET stations following this event (Fig. 1).

3. ANALYSIS AND RESULTS

Dense seismic arrays in Taiwan and Japan are able to record near-source strong ground motions from large earthquakes, and these observations have been employed to reconstruct 2-D wavefields that show seismic-wave propagation near the source region (Huang 2000; Huang et al. 2009; Furumura et al. 2011). During the 2011 Tohoku Earthquake, strong ground motions in northern Honshu were well recorded by dense stations of K-net/KiK-net with absolute timing (Fig. 1). These data can be used to reconstruct the spatial wavefields (snapshots).

In this study, to enhance the coherence of the characteristics of seismic-wave propagation, the recorded accelerograms were converted to velocity seismograms and a band-pass filter was applied with corner frequencies of 0.02 and 0.05 Hz, prior to further analysis. The spatial wavefields were interpolated from the common-time amplitudes of records (Huang 2000). Figure 2 shows an example of a snapshot of seismic-wave propagation, showing the instantaneous, vertical velocity distribution at 100 seconds after the onset of the source rupture. The same procedure as that used to construct Fig. 2 was applied to other selected times, and serial snapshots were reconstructed at set time intervals (Fig. 3). The snapshots provide a time history of the spatially dependent wavefields.

Each panel in Fig. 3 shows a vertical velocity image of ground motion at a given time. Taken together, the panels show the progressive build-up of ground motion, the seismic energy radiating from the rupture plane, and the propagation of disturbances and wavefronts over the entire seismic array. Waveform analysis can then be applied, based on serial discrete snapshots at equal time intervals. Alternatively, the surface ground motion can be portrayed by generating an animation using successive snapshots with a short time interval. Such an animation would enable the uninterrupted

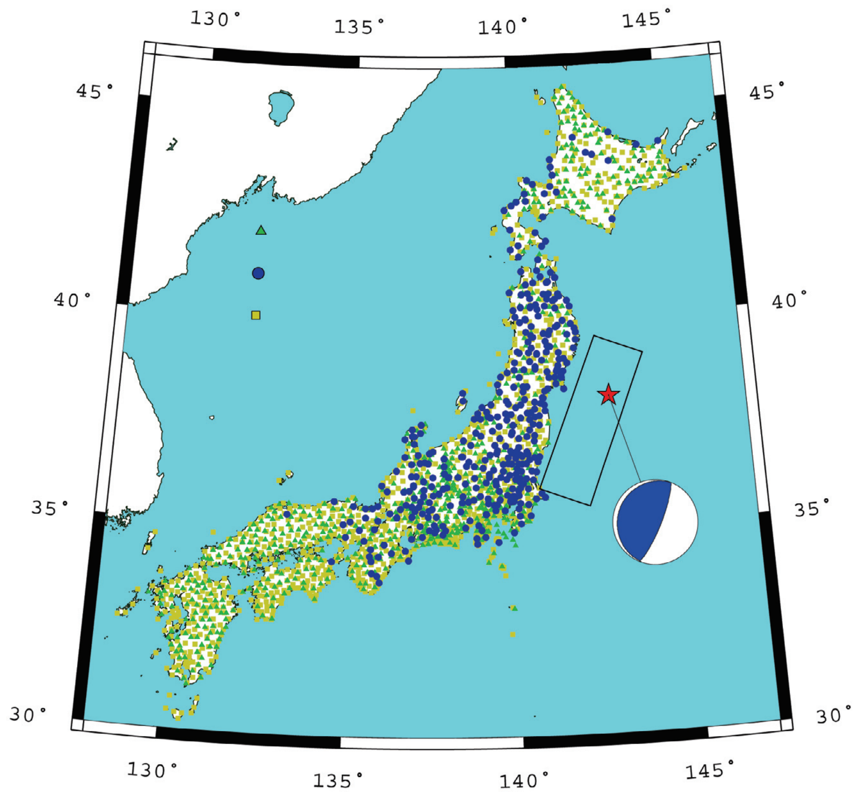

Fig. 1. Distribution of seismic stations of the National Research Institute for Earth Science and Disaster Prevention (NIED)'s Hi-net (filled triangles) and K-net/KiK-net (dots) networks, and receiver stations (filled squares) of the GPS Earth Observation Network (GEONET) GPS array. The red star shows the epicenter of the 2011 off the Pacific coast of Tohoku Earthquake, and the open rectangle represents the proposed fault rupture area of this event (modified from ERI, 2011).

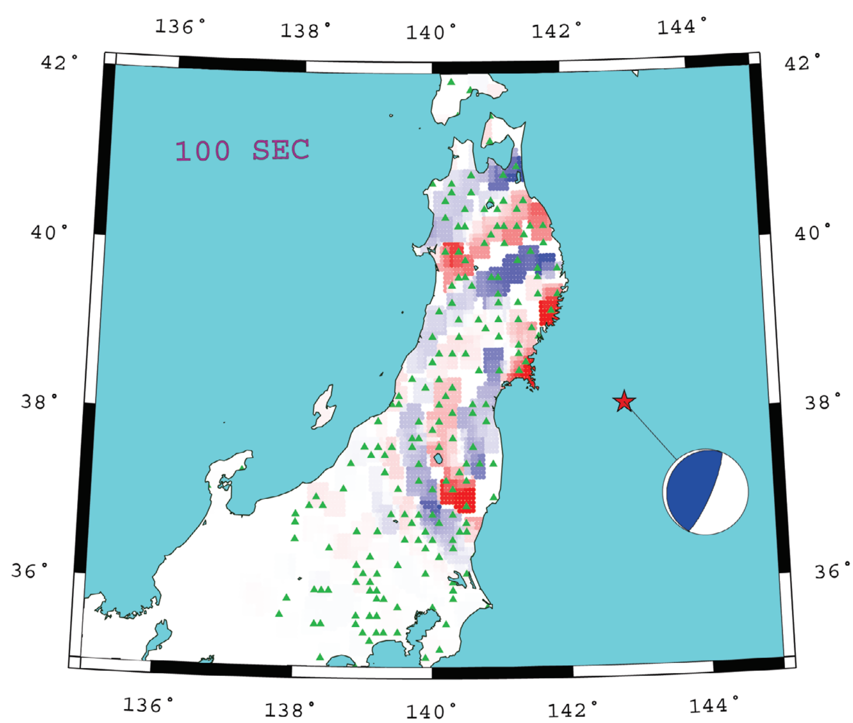

Fig. 2. Snapshot of seismic-wave propagation using data of K-net/KiK-net (NIED). The amplitude of the vertical component (velocity) is indicated by color (red = upward; blue = downward). The red star shows the epicenter of the 2011 off the Pacific coast of Tohoku Earthquake, and green triangles indicate observation stations used for this analysis. The time at upper left indicates the time from the earthquake origin.

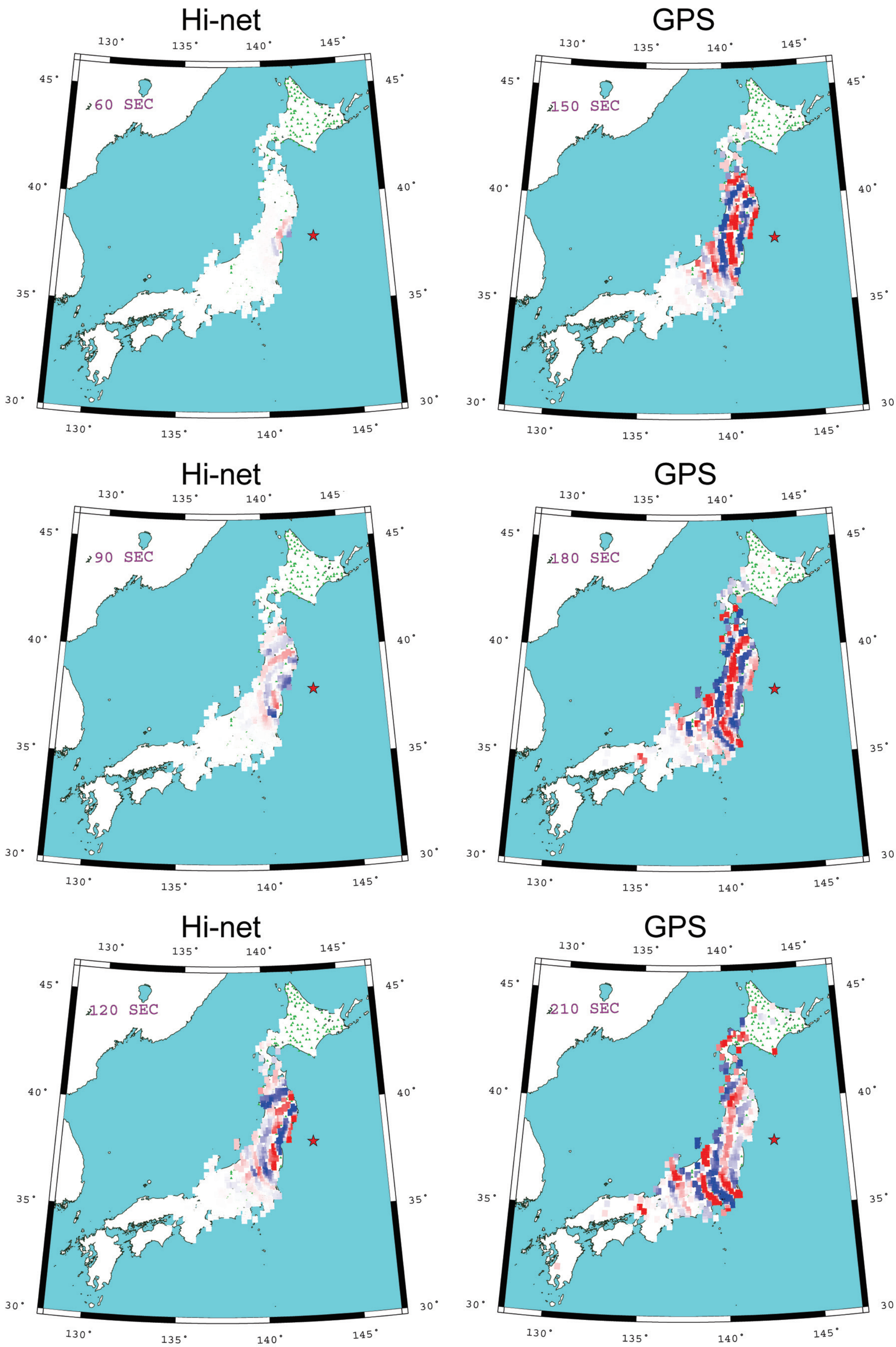

Fig. 3. Snapshots of the ground motions (velocity) over Japan after the Tohoku Earthquake (time interval, 30 s). For an explanation of symbols, etc., see Fig. 2.

observation of ground motions, the radiation of seismic energy from the rupture plane, and the propagation of disturbances and wavefronts over the Earth's surface.

GPS-recorded information is more complex than a time series recorded by a seismic station, as each GPS station receives multiple messages from different satellites. Each GPS satellite transmits carriers at two frequencies in the L-band (1.2 and 1.5 GHz), in order to assess the difference in time delay when the transmissions penetrate the ionosphere and remove the uncertainty of GPS measurements from ionosphere. However, the correction part of time delay contains information on spatial variations in the properties of the ionosphere, i.e., TEC changes (for details, see Calais et al. 1998; Lognonné et al. 2006).

In the present study, we considered that the STID induced a TEC change. Using a similar procedure to that of demultiplexing for seismic array data, GPS data can be separated into time series for numerous satellite-station pairs. Each time series is considered as an STID induced by a thin ionosphere perturbation at heights of up to 350 km (as assumed in this study). To enhance the coherence of the characteristics of seismic-wave propagation, the recorded STIDs were subjected to a band-pass filter with a window of 3 - 9 min (0.0056 to 0.0019 HZ), prior to further analysis. In contrast to the fixed location of a ground-based seismic station, the response location in the ionosphere (i.e., the sub-ionospheric point, SIP) changes over time according to the satellite's location (Fig. 4). We considered this special situation and processed all the STID time series in the same way as seismic array data; we reconstructed a series of 2-D wavefields (snapshots) to show the propagation of seismic waves in the ionosphere.

Within the 2-hour record following the onset of the mainshock for a given event, several satellites can be above the epicenter providing data that can be used to examine seismic waves in the ionosphere. However, in this study, we compared the common seismic-wave excitation recorded on the ground and in the ionosphere. Hence, only observations from GPS Satellite 15 are analyzed because this satellite was traveling across the northern part of the Japan region during the 2011 earthquake (Fig. 4). Figure 5 shows selected snapshots at several time steps. Each panel in Fig. 5 represents the STID at a given time. These snapshots provide a time history of the spatially dependent wavefields, showing the propagation of seismic waves in the ionosphere. This is the first time that such data have been compared with snapshots of ground motion (Fig. 3) in an effort to trace the rupture process of an earthquake source.

The same procedure was employed to reconstruct snapshots of ground motions using Hi-net data (Fig. 6). Because the seismograms were recorded by short-period sensors, the near-source wavefields show high-frequency and complex scattering compared with K-net/KiK-net data; however, in areas far from the source region, the sensitive Hi-net snapshots show coherent wavefield propagation in the southern Honshu region, where no K-net/KiK-net data were recorded.

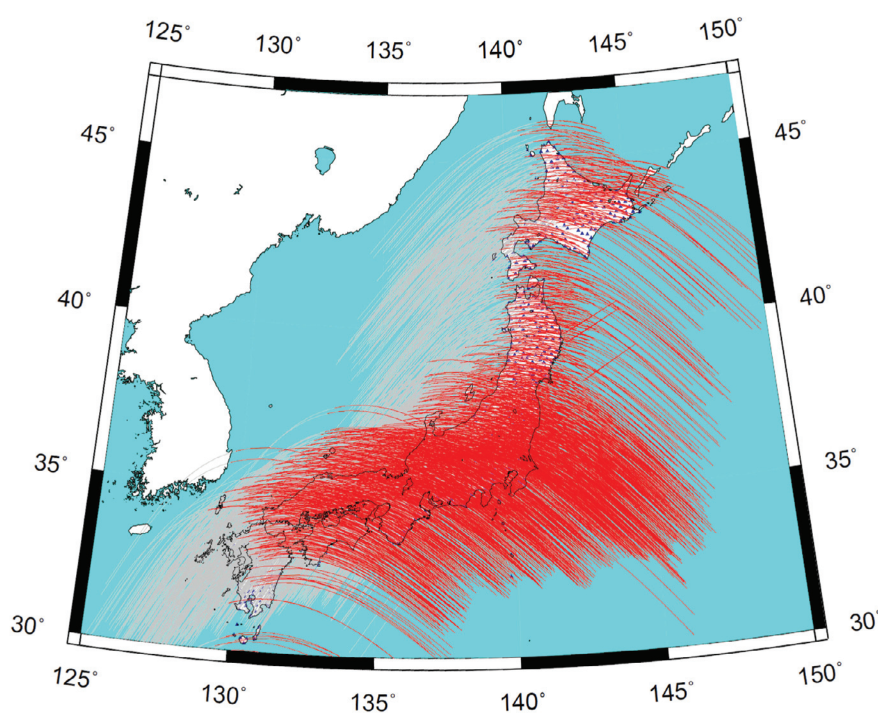

Fig. 4. SIP trajectories for GPS Satellite 15, calculated assuming a thin ionosphere as high as 350 km. Grey and red lines show the individual SIP trajectories of GEONET GPS receiver stations (used in this study) for the 2 hours before and after the earthquake origin, respectively.

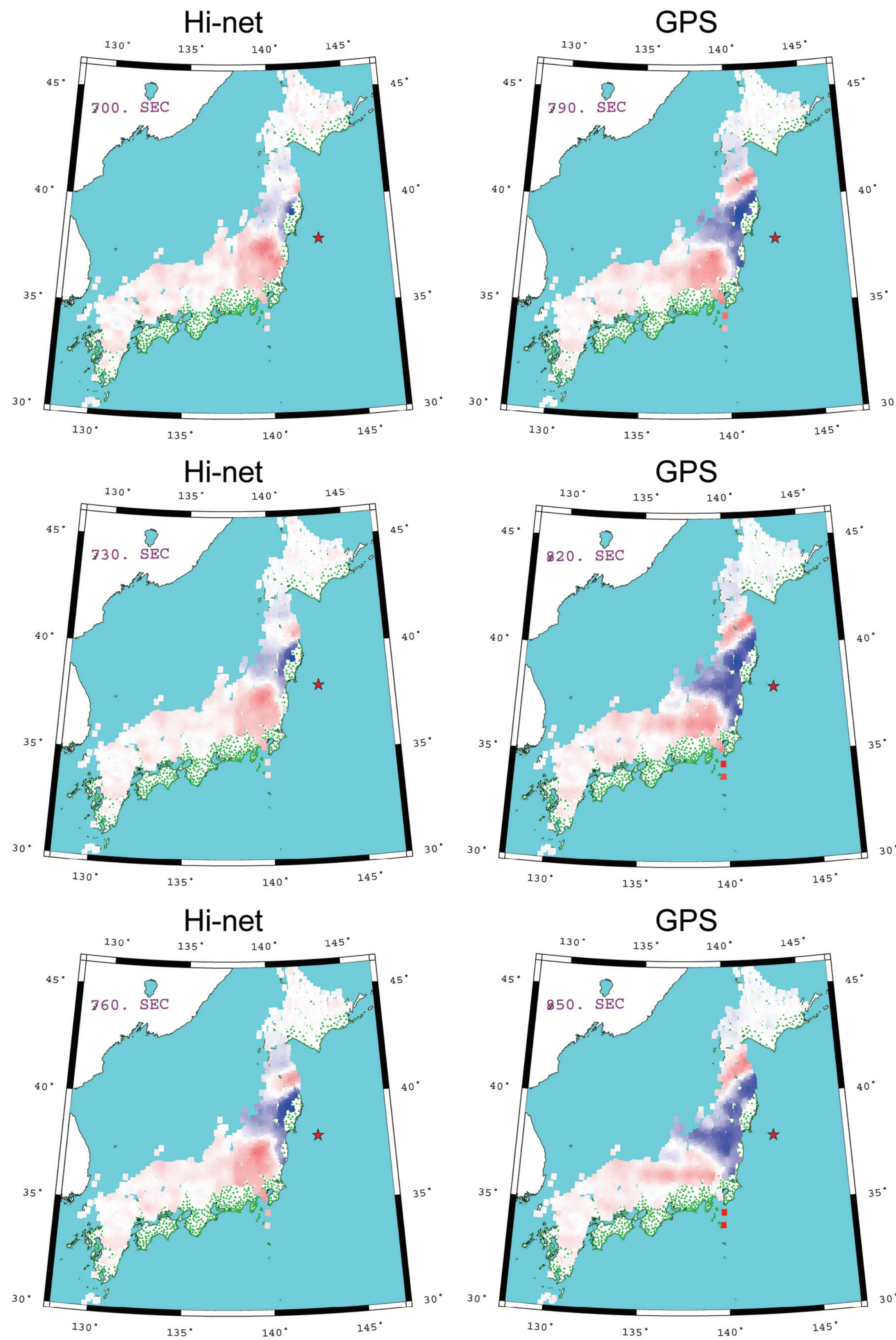

Fig. 5 Snapshots of the propagating STID for GPS Satellite 15 after the 2011 Tohoku Earthquake. The red star indicates the epicenter, and green triangles represent GPS receiver stations used in this study. The amplitude of the wavefield is shown by color (red = upward, blue = downward). The time at upper left in each panel is the time from the earthquake origin.

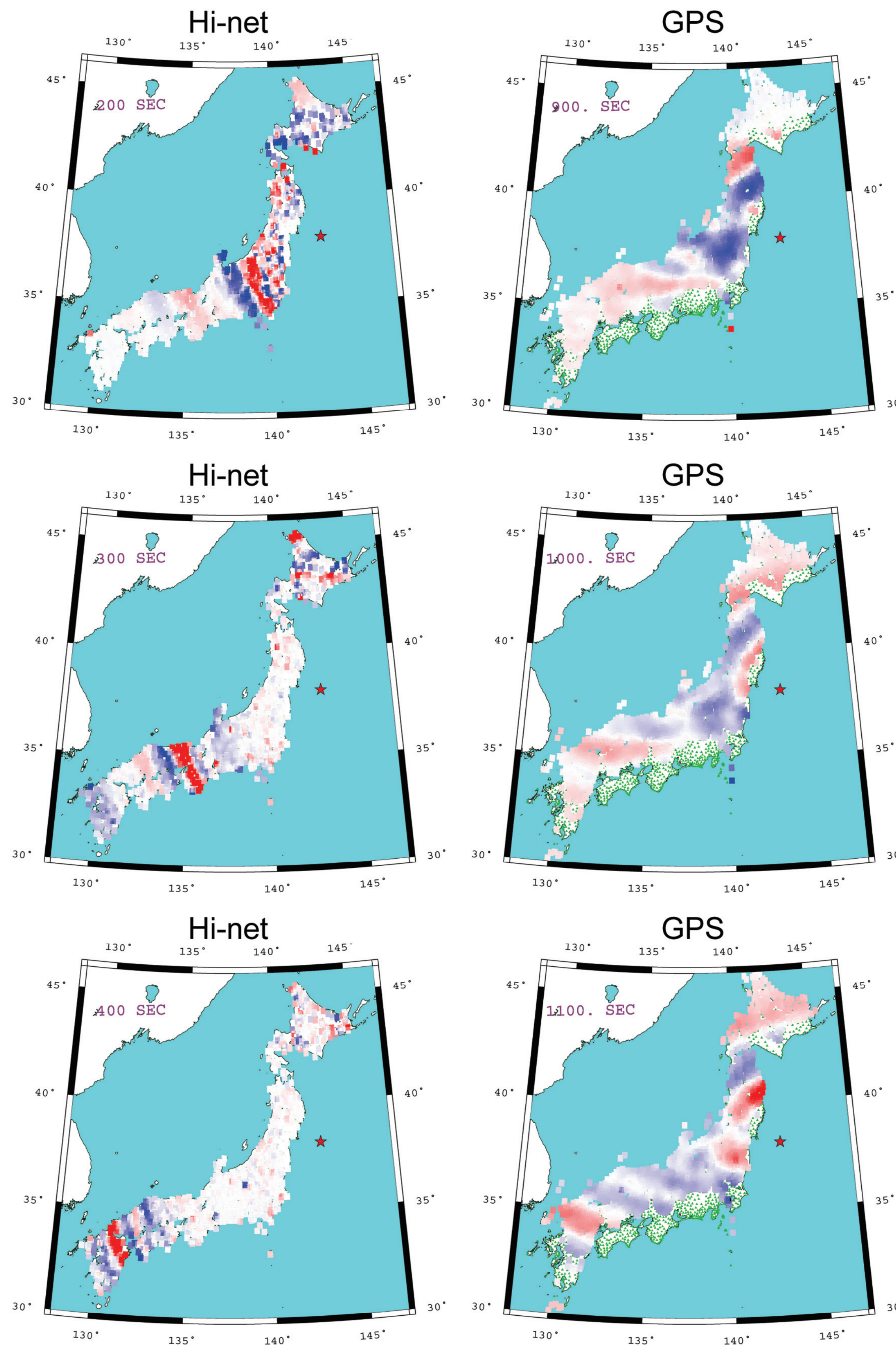

Fig. 6. Snapshots of ground motions determined from Hi-net data (upper three panels) and of propagating STID from GPS Satellite 15 (lower three panels) following the 2011 off the Pacific coast of Tohoku Earthquake. The time at upper left in each panel is the time from the earthquake origin. The snapshots cover the period of major energy release from the source.

Figure 6 also shows snapshots of the propagation of seismic waves on the ground and in the ionosphere, at sites far from the source region.

4. DISCUSSION AND CONCLUSIONS

The snapshots reconstructed at a high temporal resolution show the propagation of the coherent near-source waveforms of ground motions and ionospheric perturbations related to the 2011 Tohoku Earthquake. Some of the complex wavefronts from surface ground motions (Figs. 3 and 6) may have been induced by multiple source asperities upon the fault plane or by soft-soil amplification at the station site. However, the propagating seismic waves in the ionosphere show a simpler wavefront than surface ground motions, possibly due to differences in the analyzed frequency band used to construct the snapshots.

The ground and ionosphere perturbations are initially characterized by symmetric circular wavefronts spreading from the hypocenter, although the circular shape of wavefronts, which radiated from the epicenter, becomes gradually distorted when the source rupture is extended. The successive snapshots of surface ground motions show that the radiation of seismic energy was relative minor during the first 60 seconds following rupture; the bulk of the seismic energy was radiated from the source within 180 sec of initiation of the rupture (Fig. 3). The STID was first detected by the GPS array at 650 seconds after the earthquake occurrence. The duration of the source rupture was not clearly determined from STID snapshots, due to the continuous oscillations observed from the source region (Figs. 5 and 6). In the case of the continuous propagation of seismic waves after the source rupture, the major discrepancy between the ground and ionosphere snapshots (Fig. 6) is due to the contrasting propagation velocities of seismic waves in the two media. The coherent wavefronts from the two sets of analyses show different propagation directions, possibly due to the presence of lateral heterogeneities in the respective media.

The results of this study may contribute to studies of earthquake sources and seismic-wave propagation, and complement the inversion of observed waveforms performed to understand the kinematics of earthquake ruptures. Although the resolution of images of seismic-wave propagation in the ionosphere is currently inferior to that of images of seismic-wave propagation in the Earth, the resolution may be improved in the future if we make use of GPS data with a high sampling rate. Furthermore, SIP located within 500 - 600 km of GPS receiving sites (Heki and Ping 2005) can provide seismic-wave observations over oceanic areas, as with tsunami monitoring, which cannot be achieved using data from land-based seismic networks.

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