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LETTER — Earth Planets Space, **63**, 547–551, 2011

Outline of the 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0) —Earthquake Early Warning and observed seismic intensity—

Mitsuyuki Hoshiba[1], Kazuhiro Iwakiri[1], Naoki Hayashimoto[1], Toshihiro Shimoyama[2], Kazuyuki Hirano[2], Yasuyuki Yamada[2], Yuzo Ishigaki[2], and Haruyuki Kikuta[2]

[1]*Meteorological Research Institute, Nagamine 1-1, Tsukuba 305-0031, Japan*
[2]*Japan Meteorological Agency, Ohtemachi 1-3-4, Chiyoda-ku, Tokyo 100-8122, Japan*

(Received April 12, 2011; Revised May 21, 2011; Accepted May 22, 2011; Online published September 27, 2011)

The 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0) that occurred on March 11, 2011, caused strong ground motion around northeastern Japan. Before the strong ground motion hit cities, the Japan Meteorological Agency (JMA) issued Earthquake Early Warning (EEW) announcements to the general public of the Tohoku district and then the warning was automatically broadcast through TV, radios and cellular phone mails. The EEW was earlier than the S wave arrival and more than 15 s earlier than the strong ground motion (intensity 5-lower or greater on the JMA scale) everywhere in the district. Seismic intensity 7 was observed for only the second time since JMA introduced instrument-based observation for intensity measurements in 1996. Intensities of 6-upper and 6-lower were widely observed at many stations in the Tohoku and Kanto districts, over an area of approximately 400 km × 100 km. The duration of strong ground motions was quite long. For the Tokyo region, JMA EEW expected intensities of 4, which was an underestimation of the observed intensity (5-upper). This underestimation can probably be attributed to the large extent of the fault rupture.

Key words: The 2011 off the Pacific coast of Tohoku Earthquake, strong ground motion, seismic intensity, Earthquake Early Warning.

1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0) occurred off the pacific coast of Japan on March 11, 2011, and caused a huge tsunami that killed more than 12,000 people, and left more than 12,000 people missing (Fire Disaster Management Agency, Japan, report of April 11, 2011). Strong ground motion was also recorded across a wide area of northeastern Japan. Just before the strong ground motion hit cities in the Tohoku district (northeastern Honshu Island), the Japan Meteorological Agency (JMA) issued the Earthquake Early Warning (EEW) announcements to the general public in the district. Seismic intensity of 7 (JMA scale) was observed, for only the second time since JMA introduced instrument-based intensity observations in 1996 (Hoshiba *et al.*, 2010). Seismic intensities of 6-upper and 6-lower were also widely observed in the Tohoku and Kanto (central eastern Honshu) districts.

This paper outlines the warnings of strong ground motion (that is, EEW) and observations of the seismic intensity for the M_w 9.0 earthquake.

2. Observation of Seismic Intensity and Operation of JMA EEW

In Japan, the JMA intensity scale is widely used to measure seismic intensity. Since 1996 this scale has been based on instrumental measurements in which not only the amplitude but also the frequency and duration of the shaking are considered (JMA, 1996; Hoshiba *et al.*, 2010). The 10-degree JMA intensity scale rounds off the instrumental intensity value to the integer. Intensities of 5 and 6 are divided into two degrees, namely 5-lower, 5-upper, 6-lower and 6-upper, respectively. Intensity 1 corresponds to ground motion that people can barely detect, and 7 is the upper limit. At present, seismic intensity is measured at more than 4,000 places throughout Japan by JMA, municipalities, local governments and the National Research Institute for Earth Science and Disaster Prevention (NIED). When an earthquake occurs, the intensity data are transmitted to JMA and summarized. The summary is broadcast through multiple media starting within two minutes after the earthquake, and it is updated as the data increase.

EEW aims at mitigating an earthquake disaster by giving people enough time to take appropriate safety measures in advance of strong shaking. It has been operational nationwide in Japan by JMA since October, 2007. For JMA EEW, the hypocenter is determined by a combination of several techniques (Hoshiba *et al.*, 2008), using approximately 1,100 stations from the JMA network and the Hi-net network of NIED; magnitude is mainly from maximum displacement amplitudes (Kamigaichi *et al.*, 2009). The JMA EEWs are divided into two grades: "forecast" and "warning" (Hoshiba *et al.*, 2008; Kamigaichi *et al.*, 2009; Doi, 2010). The EEW "forecast" is issued to advanced users when events are estimated to be M 3.5 or larger, or when the expected seismic intensity is 3 or greater. In the "forecast",

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doi:10.5047/eps.2011.05.031

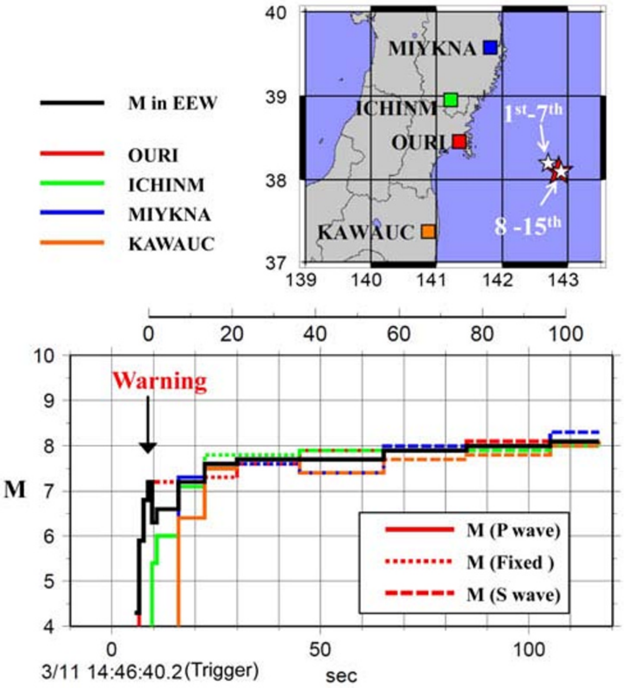

Fig. 1. Sequence of determinations of epicenter and magnitude in JMA EEW. Upper right panel: epicenters determined by the EEW system are shown as a white star for the first to seventh "forecast" (5.4–11.0 s after the first trigger) and another for the next eight (15.9–116.8 s). Focal depth was estimated to be 10 km for all 15 announcements. Red star indicates the epicenter location from the unified JMA catalog (focal depth is 24 km). The resolution of the JMA EEW system is 0.1 degree for latitude and longitude, and 10 km for focal depth for hypocenter determination. Lower panel: magnitudes estimated from maximum displacement amplitude at four stations. Color lines represent the different stations; the black line is the median value, which is used for JMA EEW. Bottom axis shows the elapsed time from the first trigger, and offset axis at top shows time elapsed from the EEW "warning" (the fourth "forecast"). The solid line indicates the magnitude of the P wave, broken line is that of S wave, and dotted line shows the period during which the magnitude is kept unchanged around the S wave arrival.

the regions are particularly specified where seismic intensity 4 or greater is expected. When intensity is expected to be 5-lower or greater at any observation station of the seismic intensity networks, "warning" is issued to the general public in regions where intensity 4 or greater is expected. The "warning" is broadcast in various ways, such as by TV, radio and cellular phone mails. JMA EEWs are updated as available data increases with elapsed time. Accordingly EEWs are issued repeatedly with improving accuracy. The "warning" is updated when the seismic intensity is expected to be 5-lower or greater in regions where the intensity was estimated to be less than 4 in the first "warning": that is, where new regions are subject to shaking above the threshold. Even when the update causes the expected intensity to fall below 5-lower at any stations, the "warning" is not canceled so as to avoid confusion if the expected intensity rises again. In the updated "warning", the newly added regions are described. At present operation, an update of the "warning" is given only when the elapsed time is less than 60 s from the first trigger, to avoid too late a warning due to the fluctuation of gradually increasing amplitude of later phases (e.g., M 5.8 events of May 8, 2008; JMA, 2008).

3. EEW during the M_w 9.0 Earthquake

The JMA EEW system was triggered for the M_w 9.0 earthquake when station OURI detected the initial P wave at 14:46:40.2, Japan Standard Time, March 11 (JMA, 2011a, b). The first EEW "forecast", the first of 15 announcements, was issued 5.4 s later. The magnitude at the time was estimated to be 4.3, because the waveform started with small amplitude, which was comparable to noise level for displacement (Hoshiba and Iwakiri, 2011). The small amplitude does not indicate that the initial rupture of the M_w 9.0 event is large, and does not suggest a large magnitude event. Figure 1 shows the sequence of hypocenter and magnitude updates for the earthquake. For the M_w 9.0, hypocenter of Horiuchi *et al.* (2005)'s technique was adopted using data from Hi-net, and the magnitude was estimated from the four stations shown in Fig. 1. By the fourth "forecast", 8.6 s after the first trigger, the magnitude was estimated to be 7.2 and seismic intensity was expected to be 5-lower for central Miyagi prefecture (around Sendai city) and the fourth "forecast" was a "warning" to the general public in the Tohoku district. Then it was automatically broadcast through TV, radios and cellular phone mails. NHK, a non-profit broadcasting company, broadcast it nationwide, and other TV companies did so locally. The "warning" was earlier than the S wave arrival (observed intensity was at most 2) and also 15 s earlier than the time that strong ground motion (intensity 5-lower) hit the closest station to the epicenter (Fig. 2). The animation of the performance is shown in the Meteorological Research Institute (2011). The reason the magnitude decreased during the fifth through seventh "forecast" (9.6–15.9 s after the first trigger) was small magnitude estimated at the second station, ICHINM, due to the small amplitude of the initial part of the event. By the issue of fifteenth "forecast", 116.8 s after the first trigger, the magnitude was estimated to be 8.1. This estimated magnitude is almost the upper limit of JMA displacement magnitude because of amplitude-magnitude saturation for events of $M_w > 8$. Note that the displacement magnitude is estimated from maximum displacement amplitude which corresponds to the outputs of seismometers having eigenperiod of 6 s, and the mainshock displacement magnitude is 8.4 in the unified hypocenter catalog of JMA (Hirose *et al.*, 2011).

4. Observed Seismic Intensity of the M_w 9.0

Figure 3 shows the distribution of the observed seismic intensities of the March 11 mainshock, and the 2003 Tokachi Oki earthquake (M_w 8.0). The intensity contours are based on the observed intensities from the dense seismic intensity networks after taking into account the site amplification factors, which is similar to the idea of ShakeMap (Wald *et al.*, 2006). The area of strong ground motion (6-upper and 6-lower) extends from the Tohoku to the Kanto district, over an area of approximately 400 km × 100 km, which is much larger than the corresponding area of the 2003 Tokachi Oki earthquake. K-NET station MYG004 in Kurihara city, at which intensity 7 was recorded, is 175 km from the epicenter, and some stations at which 6-lower intensity were observed in the Kanto district are more than 350 km from the epicenter.

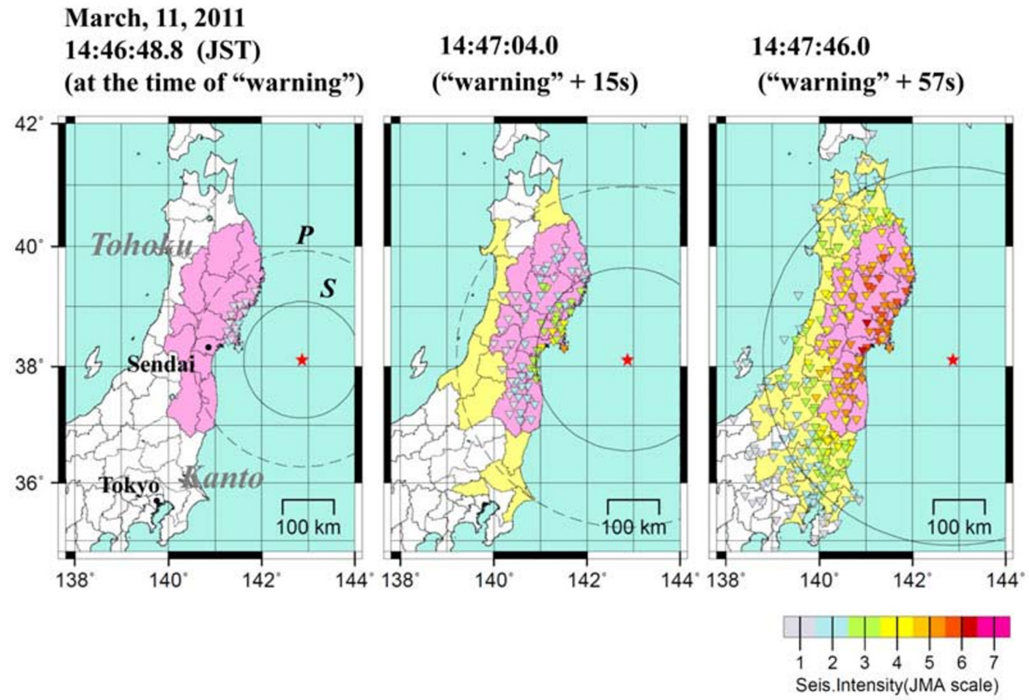

Fig. 2. Region of EEW "warning" and "forecast", and distribution of seismic intensities estimated in real time manner (Kunugi *et al.*, 2008) at 14:46:48.8 when the "warning" was issued (left), at 14:47:04.0 when intensity 5-lower or greater first appeared (center), and at 14:47:46.0 when the Tokyo region was first specified in the EEW "forecast" (right). Pink area indicates the region where the "warning" was issued, and the yellow areas are those specified in the "forecast". Wave fronts of P and S waves are shown by broken and solid circles, respectively. The seismic intensities (colored triangles) were measured using waveforms of the K-NET, KiK-net (NIED), and JMA networks. The animation of this figure is shown in the Meteorological Research Institute (2011). The distribution of the eventual seismic intensity, which means finally observed intensity, is shown in Fig. 3.

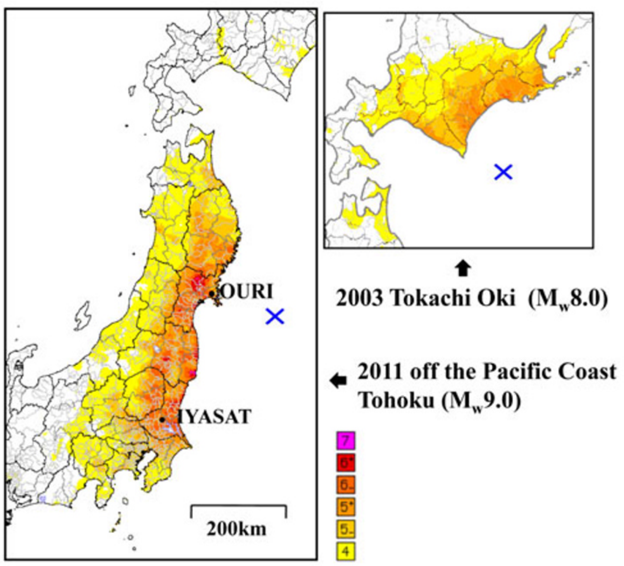

Fig. 3. Seismic intensity distribution of the 2011 M_w 9.0 earthquake and the 2003 Tokachi Oki earthquake (M_w 8.0).

In addition to the wide area of strong ground motion, a long duration was characteristic of the event. Figure 4 shows the acceleration at stations OURI (relatively near the epicenter, 138 km) and IYASAT(relatively far, 315 km), along with the seismic intensity measured in real-time manner using Kunugi *et al.*'s (2008) method. For comparison, acceleration and intensity at KiK-net station IWTH25 are also shown at the time of the 2008 Iwate-Miyagi Nairiku earthquake (M_w 7.0, 3 km). At OURI, two peaks are apparent in the acceleration envelope, which is probably due to the complicated source process. The second peak was 50 s after the first peak. At IYASAT, strong ground motion was apparent from later phases, well after the direct S phase, and it took 80 s to increase from intensity 1 (barely felt) to 5-lower, the level at which most people were frightened. The duration is very long as compared to 1 s which was observed at IWTH25 at the M_w 7.0 event. Ground motions corresponding to intensity 4, or greater, continued for 120 to 190 s at many observation stations in the Tohoku and Kanto districts (JMA, 2011c).

The EEW system expected intensity of 4 in the Tokyo region in the twelfth to fifteenth (final) issues (Fig. 2). This was an underestimation. Actual observations reached 5-upper, which is greater than the criterion of the EEW "warning". The underestimation can probably be attributed to the large extent of the later fault rupture. For the northern part of Ibaraki prefecture (around IYASAT), where intensity expected in the first warning (fourth "forecast") was less than 4, the expected intensity rose to 5-lower by the fourteenth "forecast", but it was too late to update the "warning", because it was issued 105 s after the trigger, which is later than the 60 s criteria at which upgrades are stopped.

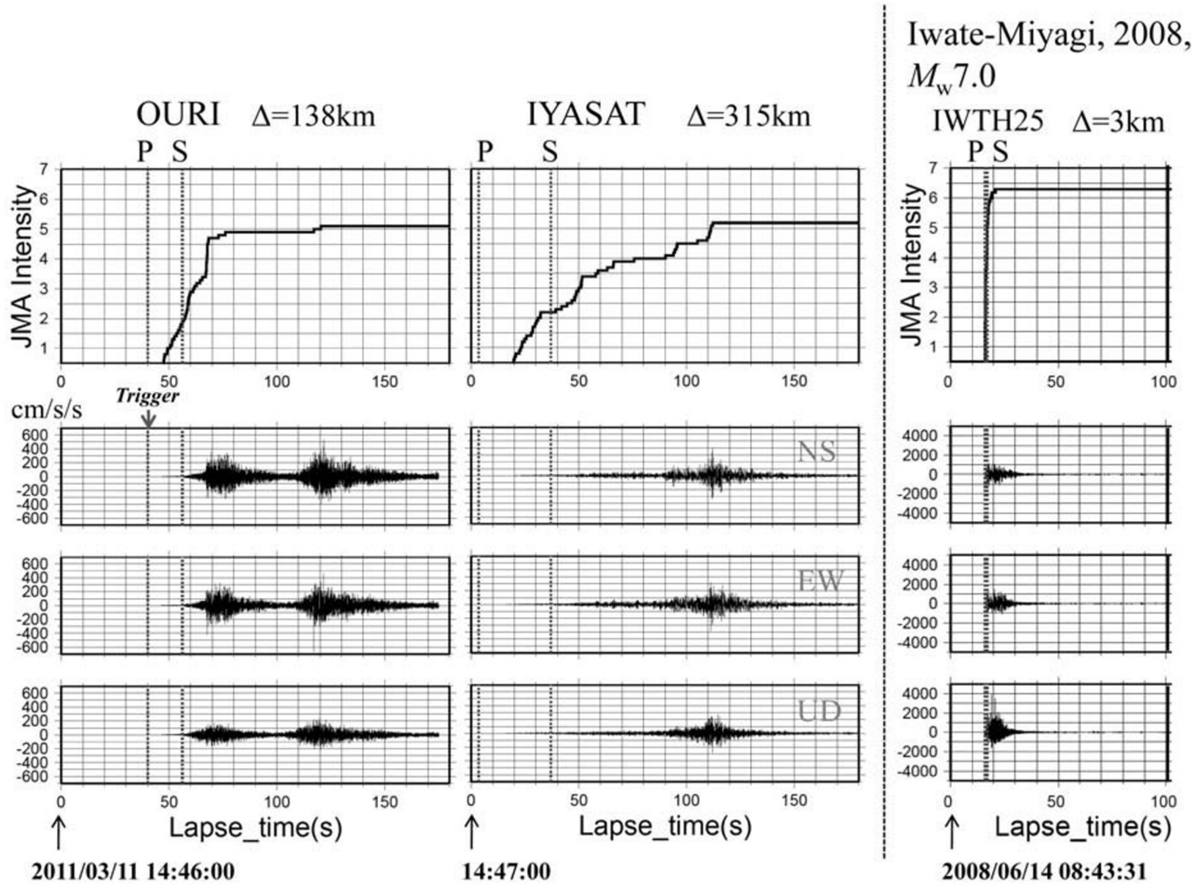

Fig. 4. Acceleration waveform and seismic intensity estimated in real-time manner at OURI and IYASAT. *P* and *S* wave arrival times are shown by dotted lines. The arrow labeled "Trigger" indicates 14:46:40.2, when station OURI triggered the EEW procedure. For comparison, acceleration and intensity at IWTH25 (KiK-net) are also shown at the time of the 2008 Iwate Miyagi Nairiku earthquake (June 14, 2008, focal depth is 8 km, M_w 7.0).

5. Summary and Remarks

The 2011 Tohoku Earthquake (M_w 9.0) generated widespread strong ground motion, and seismic intensities of 6-lower and 6-upper were recorded in the Tohoku and Kanto districts over an area of approximately 400 km × 100 km. The durations of strong ground motion were very long.

The JMA EEW system issued one "warning" to the general public in the Tohoku district before the start of strong ground motion. It was earlier than the *S* wave arrival and 15 s earlier than strong ground motion (intensity 5-lower or greater) at the closest station to the epicenter.

After the mainshock, the EEW system did not work well for several hours because of high background noise from the coda waves of the mainshock and active aftershocks, and because of power failure and wiring disconnections. For several days, when earthquakes sometimes occurred simultaneously over the wide source region, the system became confused, and did not always determine the location and magnitude correctly. In 19 days from the mainshock to March 29, 2011, JMA appropriately issued EEW "warning" for 15 of the 22 events for which seismic intensity 5-lower or greater was actually observed. On the other hand, during the same time, 45 EEW "warnings" were issued, but actual observed intensities did not exceed 2 at any observation stations in 11 of the 45 events (JMA, 2011d).

Acknowledgments. The authors thank Dr. Stuart Weinstein, an anonymous reviewer, and Prof. K. Yomogida (editor) for their comments. Seismic intensity data were provided by JMA as well as NIED and local governments and municipalities. Waveforms were obtained from K-NET and KiK-net of NIED, and the unified hypocenter catalog and CMT catalog of JMA were used. We thank all of these entities for their effort in maintaining these observations and providing the data during very trying times. The JMA EEW uses a combination of several techniques developed by joint research with the Japan Railway Technical Research Institute, and also by NIED. It also uses real-time data from Hi-net of NIED in addition to JMA's own network for hypocenter determination. Figures were made using Generic Mapping Tools (Wessel and Smith, 1995).

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M. Hoshiba (e-mail: mhoshiba@mri-jma.go.jp), K. Iwakiri, N. Hayashimoto, T. Shimoyama, K. Hirano, Y. Yamada, Y. Ishigaki, and H. Kikuta