Evaluation of the real-time earthquake information system in Japan

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[1] The real-time earthquake information system (REIS) of the Japanese seismic network is developed for automatically determining earthquake parameters within a few seconds after the P-waves arrive at the closest stations using both the P-wave arrival times and the timing data that P-waves have not yet arrived at other stations. REIS results play a fundamental role in the real-time information for earthquake early warning in Japan. We show the rapidity and accuracy of REIS from the analysis of 4,050 earthquakes in three years since 2005; 44 percent of the first reports are issued within 5 seconds after the first P-wave arrival and 80 percent of the events have a difference in epicenter distance less than 20 km relative to manually determined locations. We compared the formal catalog to the estimated magnitude from the real-time analysis and found that 94 percent of the events had a magnitude difference of ±1.0 unit.
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1. Introduction

[2] If the location and source parameters of a large earthquake could be determined the instant it occurred, then evacuations and emergency actions can be undertaken before the arrival of the S-waves, which would greatly mitigate the damage from the event. The system developed for this purpose, commonly called an Earthquake Early Warning System (EEWS), is reported as SAS in Mexico [*Espinosa-Aranda et al.*, 1995], as VSN in Taiwan [*Wu and Teng*, 2002], as IERREWS in Turkey [*Erdik et al.*, 2003], and as ElarmS in California [*Allen and Kanamori*, 2003].

[3] In Japan, several kinds of practical EEW systems have been developed to reduce earthquake hazards. *Nakamura* [1988] developed a system called UrEDAS (the Urgent earthquake detection and alarm system) in the early 1980s for the emergency halting of Shinkansen (bullet trains). The system provides a preliminary estimate of the epicenter of the earthquake and its magnitude using a few seconds of P-wave data recorded at a single station.

[4] Further advancement has been made in the development of an EEWS for the whole nation of Japan. The Japan Meteorological Agency (JMA) and the Railway Technical Research Institute developed a system called the Nowcast Earthquake Information System [*Hoshiba et al.*, 2008]. And the National Research Institute for Earth Science and Disaster Prevention (NIED) developed a REIS, which is able to determine hypocentral locations and earthquake magnitudes (lower-limit) automatically within a few seconds by using P-wave arrivals and also timing data (T_{now}) that P-waves have not yet arrived at other stations [*Horiuchi et al.*, 2005]. Since October 2007, the combined results of the REIS and Nowcast system have merged as an EEWS, which is being broadcast to the public in Japan. In this study, we investigate the speed and accuracy of REIS by analyzing 4,050 earthquakes with magnitude larger than 3.0 occurring in and around the Japan Islands since 2005.

2. Summary of REIS

[5] REIS is able to determine earthquake parameters and then transmit these results to JMA in order to issue an EEW. The system uses the real-time data of Hi-net, which is a seismic network comprised of about 800 highly sensitive seismometers installed throughout Japan with an inter-station spacing of 20–25 km and situated in bore holes deeper than 100 meters [*Okada et al.*, 2004]. The waveform data are recorded at 100 Hz with a 24-bit A/D converter and sent to NIED; the time delay due to processing of the data packets and their transmission is about 1.5 seconds [*Obara et al.*, 2008].

[6] To locate hypocenters as rapidly as possible, three minutes of seismographic data are stored on the shared memory, which is updated every second as new data arrives. REIS then monitors this data for evidence of earthquake occurrence by setting critical values for S/N ratios of short (1 second) and long (30 seconds) term averages of ground acceleration and absolute maximum amplitude.

[7] The hypocenter is located by a novel approach called "T_{now} method" [*Horiuchi et al.*, 2005]. Shortly after (T_{now}) an earthquake occurs at a given hypocenter location there are some stations that record P-wave arrivals and others stations which lie outside the wave front and therefore show no arrivals. If T_i is the theoretical arrival time at the station where the P-wave has not yet arrived then we formulate an inequality in which T_i is larger than T_{now}. A numerical method is used to determine a hypocenter that uses both the observed P-wave arrival times and the inequality condition for many stations outside the wave front. To scale earthquake size, we use JMA magnitude (M_{JMA}) and seismic intensity magnitude (M_I). M_{JMA} is estimated from moment magnitude by applying the Omega-square model to the seismic source spectrum [*Negishi et al.*, 2002]. M_I is a new scaling parameter for the accurate estimation of seismic intensity, which is defined from observed P-wave seismic intensity [*Yamamoto et al.*, 2008]. Hypocenter parameters obtained by the above methods are then transferred imme-

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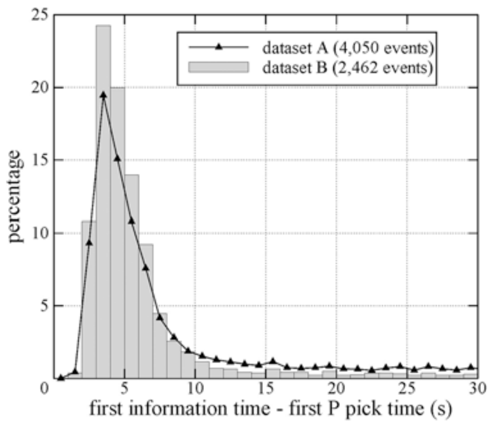

Figure 1. Histogram in percentage of the time delay of first reports. The line shows the result for 4,050 events (dataset A) with magnitude greater than 3.0 detected by REIS. Bars show the result for 2,462 events (dataset B) with hypocentral distance less than 100 km.

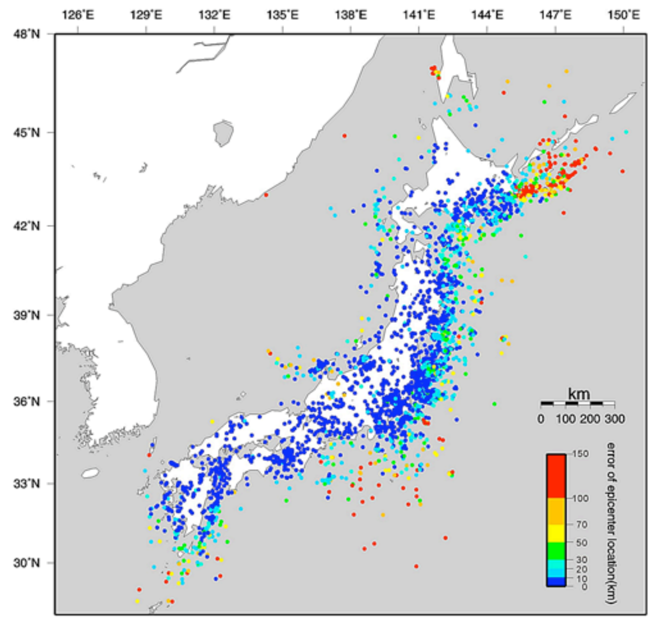

Figure 3. A map showing estimation errors of epicentral locations (dataset A). Circles show epicenters from the JMA catalog. Color shows differences of epicenters between JMA and REIS. Because of a large lateral heterogeneity in seismic velocity, the difference shows regional changes and tends to increase as epicentral distance from the network increases.

diately in XML format to JMA for broadcasting. The real-time system runs under Linux OS on a dual CPU computer (Xeon 2.8GHz) with 8 GB memory.

3. Accuracy of Estimation

[8] The REIS has detected 4,050 events with magnitude greater than 3.0 in three years since 2005. Here, we discuss the accuracy of the estimated earthquake parameters in the first reports issued by REIS.

[9] Immediate information is an important function of an EEWS. Figure 1 shows a histogram of the time delay in issuing the first report after the P-wave arrives at the closest station. Here we consider two datasets; dataset A consists of all the earthquakes detected by REIS (4,050 events) and dataset B consists of selected earthquakes from dataset A with hypocentral distances of the closest station less than 100 km (2,462 events). Clearly, dataset B does not contain far events, which usually are not damaging. Both distributions have peaks at 3–4 seconds in Figure 1; these times include the time delay due to data packaging and transmission of about 1.5 seconds. Figure 1 shows that 44 percent of

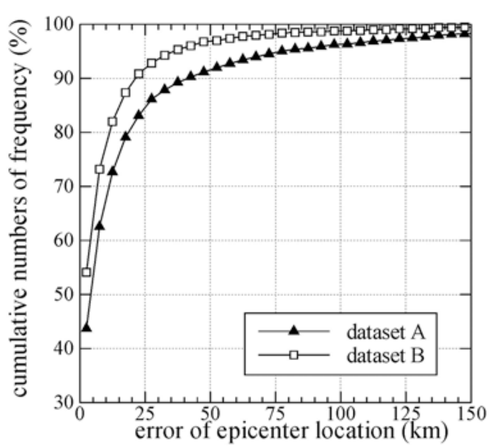

Figure 2. Cumulative histogram of differences in epicentral locations from the JMA catalog and those determined by REIS. About 80 percent of dataset A (solid triangle) and 87 percent of dataset B (open square) are within 20 km.

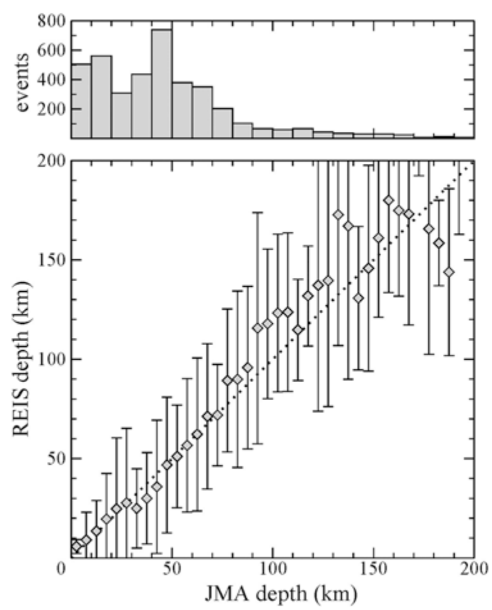

Figure 4. Comparison between the focal depths determined by first report of REIS and those obtained from the JMA catalog for dataset A. The markers show the average depths in intervals of 5 km with error bars of one standard deviation.

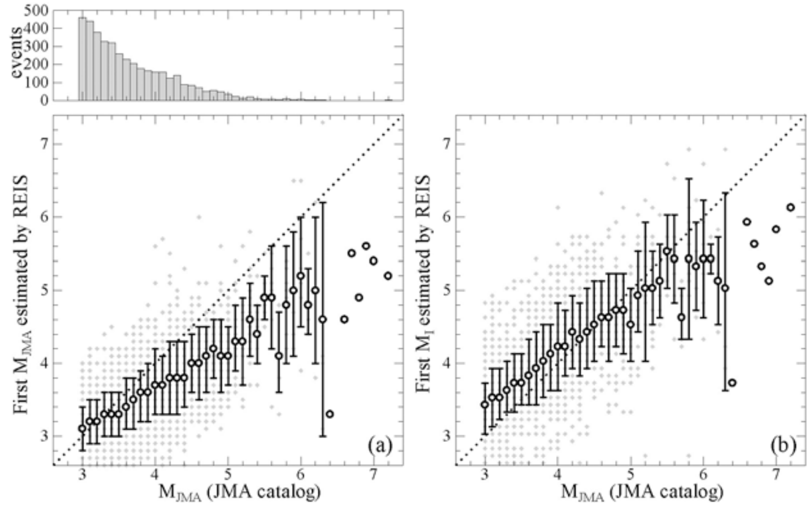

Figure 5. Plot showing the estimated average magnitude (open circle) for dataset A with error bars of one standard deviation. (a) Comparison of M_{JMA} between JMA catalog and the REIS estimate. (b) Comparison between catalog M_{JMA} and M_I estimated by REIS.

the dataset A and 55 percent of the dataset B are contained within 5 seconds. REIS will determine the hypocentral location when two stations detect P-waves for events inside the seismic network and four stations for events outside the network.

[10] Figure 2 shows the frequency distribution of the errors in epicentral location determined by REIS compared with the JMA value obtained from manually picked data using all available stations. About 80 percent of dataset A and 87 percent of dataset B have errors less than 20 km. Figure 3 shows the regional distribution of the location error. The observation seismic network is land based and therefore errors, as expected, tend to increase when earthquakes occur outside the network and especially in the far area. Figure 4 shows a comparison between focal depths estimated by the JMA data and those by REIS. The vertical lines in Figure 4 show the average estimate of depth every 5 km and the associated standard deviation. We find that heterogeneity in the seismic velocity generates large estimation errors in focal depths when P-wave arrival times from only a few stations are used.

[11] Figure 5 shows the comparison between M_{JMA} from the JMA catalog and the REIS estimate of M_{JMA} and M_I. Figure 5 shows that 73 and 67 percent have a difference less than 0.5 respectively; 94 percent of the events have differences within 1.0 in the comparison for either M_{JMA} or M_I. The difference, however, increases with magnitude. There is an apparent underestimation of M_{JMA} for large earthquakes because the first report is issued while fault rupture is still propagating. Moreover, there are cases when Hi-net seismograms close to the epicenter are clipped, but these data are still used in the determination of the lower limit of magnitude. Although coefficients to estimate M_{JMA} from seismic moment are correctly assigned [*Negishi et al.*, 2002], there is a systematic underestimation of M_{JMA} for events larger than 4.0 in the first report. This suggests that the accurate estimation of moment magnitude requires a somewhat longer amount of waveform data. *Wu et al.* [1998] show that the final magnitude can be estimated by using the linear correction equation based on the first 10 seconds of signal. This method will be effective in estimating M_{JMA}.

4. Discussion and Conclusion

[12] From the P-wave arrivals at the closest stations, we give REIS results for the errors in estimating source parameters and the times needed to issue the first report. In the three years since 2005, more than 4,000 earthquakes with magnitude larger than 3.0 were detected by the REIS and source parameters for the majority of these events were determined within 3–4 seconds after the first P-wave

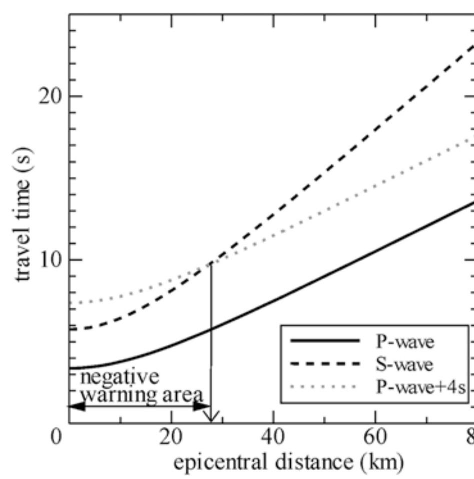

Figure 6. Travel time curve of P and S-waves for a reference focal depth of 20 km using the JMA2001 velocity model. Solid and dashed lines show P and S-wave travel times, respectively. Gray dotted line shows travel time of P-wave plus 4 seconds, which is the assumed time delay in issuing an EEW. The intersection of the dashed and dotted lines indicates the radius of the negative warning area (about 30 km). An EEW is not possible in this zone with the present REIS.

detection. About 80 percent of these events have an error in the epicenter location less than 20 km relative to manually determined locations. And our estimated magnitude for 94 percent of events has differences within 1.0 compared to the magnitude in the JMA catalog. Note that these results were from the first reports, which are mainly determined using waveform data from 4–5 stations. REIS revises the earthquake information every second, thus providing more accurate information as time increases. This information is merged with the results of JMA's Nowcast system and the resultant data are broadcast as an EEW in Japan. JMA started the practical service of EEW on October, 2007, which is a first nationwide EEWS in the world.

[13] Figure 6 shows the travel times of P and S-waves with a focal depth of 20 km. If we assume the first report is issued 4 seconds after the initial P-wave arrival, then warning times become negative within an area about 30 km from the epicenter, i.e. no EEW is possible before the S-wave arrival. When a large earthquake occurs, the closer to the hypocenter, the greater the likelihood of damage; therefore, it is very important to decrease the area of negative warning. For this purpose, *Wu et al.* [2008] show that inclusion of ocean bottom seismometers can significantly improve the warning time for earthquakes which may occur in the vicinity of the Japan Trench. Furthermore, from the point of view of shortening the processing time, introduction of on-site processing at each station would seem to be beneficial [e.g., *Odaka et al.*, 2003; *Kanamori*, 2005; *Horiuchi et al.*, 2008].

[14] As pointed out by *Rydelek et al.* [2007], earthquake magnitude is important but it is difficult to predict the magnitude of larger events from a few seconds of P-wave data. However, it is possible to track the growth in magnitude and to update this information in real-time when a large earthquake occurs.

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