The Status of Earthquake Early Warning around the World: An Introductory Overview

Richard M. Allen,[1] **Paolo Gasparini,**[2] **Osamu Kamigaichi,**[3] **and Maren Böse**[4]

INTRODUCTION

The term "earthquake early warning" (EEW) is used to describe real-time earthquake information systems that have the potential to provide warning prior to significant ground shaking. This is possible by rapidly detecting the energy radiating from an earthquake rupture and estimating the resulting ground shaking that will occur later in time either at the same location or some other location. Warning times range from a few seconds to a little more than a minute and are primarily a function of the distance of the user from the earthquake epicenter.

The concept has been around for as long as we have had electric communications (*e.g.*, Cooper 1868), but it is only in the last two decades that the necessary instrumentation and methodologies have been developed (*e.g.*, Nakamura 1988; Espinosa-Aranda *et al.* 1995). The last five years in particular have seen a rapid acceleration in the development and implementation of EEW, fueled by a combination of seismic network expansion, methodological development, and awareness of the increasing threat posed by earthquakes paired with desire by the seismological community to reduce risk.

This special issue of *Seismological Research Letters* is intended to facilitate communication of EEW methodologies and experiences in implementation. It complements the special section of *Geophysical Research Letters* published in March 2009 (Allen, Gasparini, and Kamigaichi 2009). Together, these collections of papers describe the science, engineering, and societal considerations of the active warning systems in Mexico, Japan, Taiwan, Turkey, and Romania and detail the development and testing of methodologies in the Unites States, Europe, and Asia (Figure 1). This introductory paper summarizes this content to provide an overview of EEW status around the world. We provide a summary of the various early warning methodologies and then describe the active implementation of early warning including the current users, the successes, and the failures. The Perspectives, Misconceptions, and Challenges section provides synthesis on the state of early warning around

the world, the progress made in the last few years, some of the lessons learned and misconceptions uncovered, and finally the challenges for the future.

APPROACHES TO EEW

Front Detection

All EEW systems must first detect hazardous earthquakes and then transmit a useful warning. The simplest approach to identifying when an earthquake is hazardous is to detect damaging ground shaking. The first approach to EEW was therefore to detect strong ground shaking at one location and transmit a warning ahead of the seismic energy. This concept, called front detection, was initially proposed for San Francisco following the 1868 earthquake on the Hayward fault east of the San Francisco Bay. The radiating telegraph cables could be used to signal coming ground shaking by ringing a characteristic bell above the city (Cooper 1868). This system was never implemented, but it captures the main concept of front detection by installation of seismic sensors between the earthquake source and the possible recipient of warnings. Front detection requires good knowledge of the locations of future earthquakes.

In the late 1960s, the Japanese railway systems deployed seismometers along their tracks that would trigger when the ground shaking intensity exceeded some threshold and shut off power to the trains. This approach, using "alarm-seismometers," only provides warning once serious ground shaking has started. By deploying some instruments along the east coast of Japan, between the large offshore earthquakes and the train tracks, more warning time could be gained (Nakamura 1984). All warning systems that make use of a network also use the front detection concept by detecting an earthquake in one location and providing warning to another.

When the only seismic sources are some distance from a populated area, front detection can provide significant warning times, *i.e.*, tens of seconds. The Seismic Alert System (SAS) for Mexico City uses front detection. Instruments along the coast adjacent to the subduction zone trigger on earthquakes and transmit the warning ~320 km to the city. Implemented in 1991, the SAS was the first public warning system and continues to provide ~60 s warning to Mexico City (Espinosa-Aranda

1. University of California, Berkeley
2. University of Naples (Italy)
3. Japan Meteorological Agency
4. California Institute of Technology
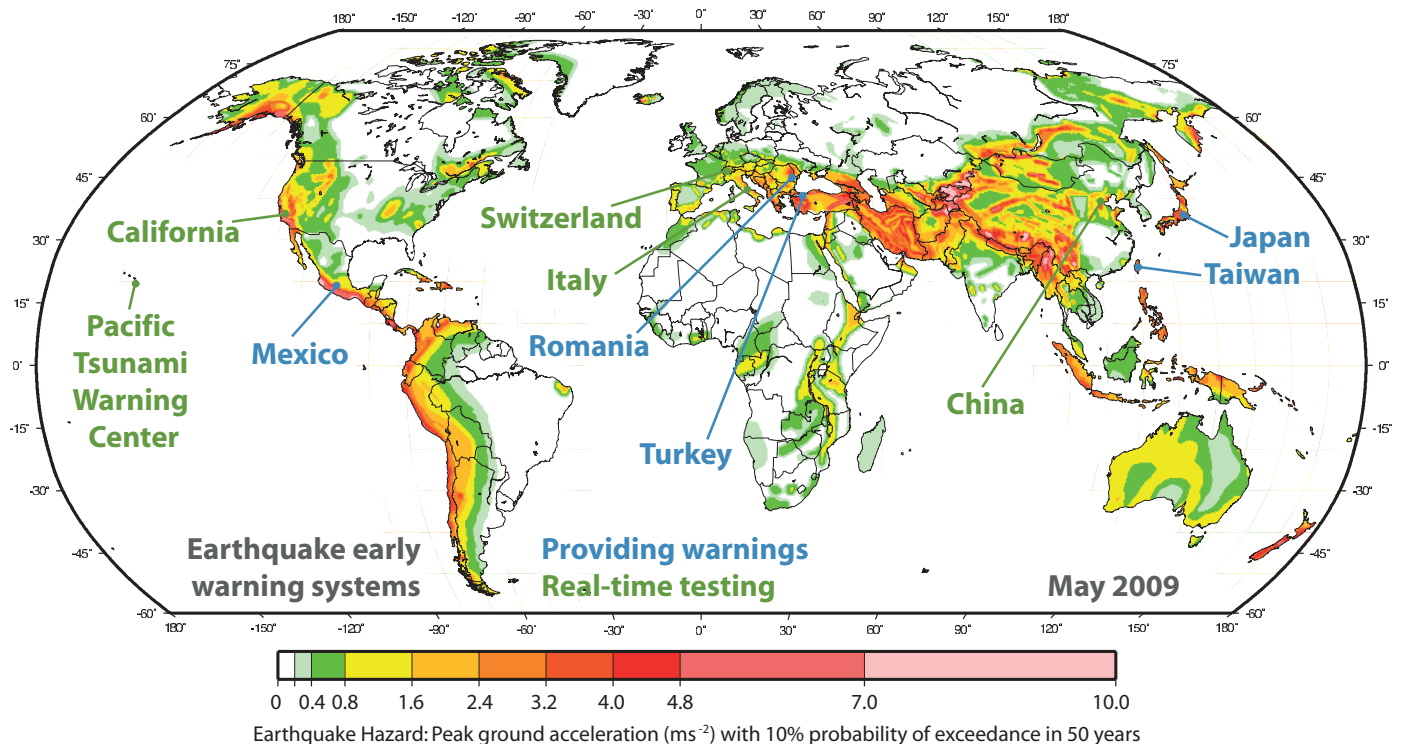
▲ Figure 1. Map of global seismic hazard showing locations where active EEW systems are providing warnings to one or more users (blue) and where EEW systems are currently being tested as part of a real-time seismic system (green).

et al. 1995). The warning system for Bucharest, Romania, uses the same concept. Seismometers in the Vrancea zone of the southeastern Carpathians detect earthquakes and provide ~25 s warning to Bucharest, which is ~160 km away (Böse *et al.* 2007). Istanbul also uses front detection. Ten instruments along the northern shore of the Marmara Sea trigger based on exceedance of an acceleration threshold at two or three sites (Alcik *et al.* 2009).

Using the *P* Wave

Waiting for strong ground shaking to be observed at one location before issuing a warning results in a large "blind-zone" around the epicenter where no warning can be provided. Given a move-out velocity of ~4 km/s for peak ground shaking following shallow earthquakes, every second of delay increases the radius of the blind zone by 4 km. Using the *P* wave to determine whether an earthquake will produce hazardous ground shaking provides additional warning. Given that the strongest ground shaking usually arrives at the time of, or after, the *S*-wave arrival, using the *P* wave to provide warning has the potential to increase the warning time everywhere, reduce the radius of the blind zone, and potentially provide warning at the epicenter.

A variety of observational parameters have been developed for using the *P* wave to assess earthquake hazard. Many are designed to estimate the magnitude of an earthquake, which can then be translated into expected ground shaking. These are discussed in this section. Others are designed to bypass mag-

nitude and to estimate the ground shaking directly; they are discussed in the following section, Onsite Warning.

One of the first *P*-wave parameters developed for early warning was the predominant period of the first few seconds of the *P* wave (Nakamura 1988). This was found to scale with the magnitude of an earthquake while remaining insensitive to the epicentral distance within a few hundred kilometers of the event. Nakamura's original method generates a continuous time series of predominant period from which the maximum value, τ_p^{max}, can be extracted and converted to a magnitude estimate (Nakamura 1988; Allen and Kanamori 2003). The advantage of this approach is that an initial magnitude estimate is available rapidly, within about one second, which can then be increased if τ_p^{max} increases. Typically, the predominant period is monitored for three or four seconds. While concern has been expressed about the stability of the measurement (Wolfe 2006), the use of τ_p^{max} has been successfully tested using earthquakes from the western United States, Japan, and Taiwan (Nakamura 2004; Lockman and Allen 2007; Tsang *et al.* 2007; Wurman *et al.* 2007; Brown *et al.* 2009, this issue). The use of τ_p^{max} is currently part of real-time system testing in California (Allen, Brown, Hellweg *et al.* 2009), Taiwan (Hsiao *et al.* 2009), and Istanbul (Fleming *et al.* 2009, this issue).

A slightly different approach to measuring the frequency content of the *P* wave was formulated by Kanamori (2005). The τ_c method calculates the effective (average) period of the *P*-wave signal over a fixed time window that is commonly selected to be three seconds. This approach shows similar scaling between τ_c and magnitude and has been tested in California and Taiwan

(Wu and Kanamori 2005a; Wu *et al.* 2007). While the $\tau_p{}^{max}$ and τ_c methods aim to characterize the same property of the *P* wave, *i.e.*, the frequency content, it has been shown that there is an advantage to using both simultaneously (Shieh *et al.* 2008). The τ_c parameter is currently part of real-time system tests in California (Böse, Hauksson, Solanki, Kanamori, and Heaton 2009), Taiwan (Hsiao *et al.* 2009), Japan, China, and at the Pacific Tsunami Warning Center in Hawaii.

The amplitude of the *P* wave is also a useful parameter for estimating earthquake hazard, provided a correction for the epicentral distance can be made. The use of the peak displacement, velocity, or acceleration of the first few seconds, typically three seconds, of the *P* wave has been shown to scale with magnitude (Wu and Kanamori 2005b; Zollo *et al.* 2006; Wu and Kanamori 2008a) and ground motion (Böse *et al.* 2007; Wu and Kanamori 2005a). The peak displacement, referred to as P_d, is usually found to be the most robust amplitude parameter provided that integration or double integration of the waveform at a station is possible. For instruments where robust calculation of P_d is not possible due to, for example, noisy accelerometers, P_v has also been shown to be useful (Wurman *et al.* 2007). P_d is currently in use by the real-time systems in California (Allen, Brown, Hellweg *et al.* 2009; Böse, Hauksson, Solanki, Kanamori, and Heaton 2009), Taiwan (Hsiao *et al.* 2009), Istanbul (Fleming *et al.* 2009, this issue), Japan, China, the Pacific Tsunami Warning Center in Hawaii, and the Campania region of southern Italy (Lancieri and Zollo 2008).

In Japan, the amplitude of the seismic waveform is used in a continuous fashion to estimate the magnitude of an earthquake. No limit on the number of seconds of *P* wave is imposed. Instead, the continuously monitored maximum amplitude of the *P*-wave displacement (vector summation of the three components) is used until the *S* wave arrives at a station. Then, a similar scaling between the amplitude of the *S*-wave displacement and magnitude is used (Kamigaichi 2004). The epicentral distance, which is necessary to translate the maximum amplitude value into magnitude, is estimated by using the first two seconds of the log-transferred *P*-wave envelope slope (*B*-delta method; Odaka *et al.* 2003).

A similar envelope function is used by several methodologies to parameterize the seismic waveforms. The peak acceleration, velocity, and displacement is calculated every second and used as an input. The Virtual Seismologist uses this data to trigger on an event and estimate the magnitude using a linear combination of the peak values (Cua and Heaton 2007). While this approach uses amplitude, a frequency dependence is introduced by the combination of acceleration, velocity, and displacement. There is therefore a similarity between this amplitude-based approach and the frequency-based methodologies described above. The neural-network based PreSEIS approach makes use either of the cumulative absolute velocity (CAV; Böse *et al.* 2008) or of other envelope parameters (Köhler *et al.* 2009, this issue) to predict seismic source and ground-motion parameters. The Virtual Seismologist and PreSEIS are cur-

rently being tested in California and Switzerland (Cua *et al.* 2009, this issue; Köhler *et al.* 2009, this issue).

Finally, the cumulative energy of the seismogram can also be used. In Mexico, the energy and growth rate are matched to similar observations from previous earthquakes and used to estimate the magnitude (Espinosa-Aranda *et al.* 1995).

One of the concerns when using the first few seconds of the *P* wave to estimate the magnitude of an earthquake is that the magnitude estimate may saturate for large magnitude events. If four seconds of *P*-wave data is being used, and the duration of an **M** 6.5 earthquake is four seconds, can *P*-wave parameters distinguish an **M** 7.5 earthquake from an **M** 6.5 event? There is clear evidence that the amplitude of the *P* wave within the first few seconds does saturate for **M** > ~7 earthquakes (Zollo *et al.* 2006; Wurman *et al.* 2007; Murphy and Nielsen 2009; Brown *et al.* 2009, this issue). To try to reduce this problem, several methodologies use longer time windows of the *P* wave and/or the *S* wave to update magnitude estimates (Zollo *et al.* 2006; Kamigaichi *et al.* 2009, this issue). When using the frequency content of the *P* wave there is less empirical evidence for saturation (Kanamori 2005; Olson and Allen 2005; Lewis and Ben-Zion 2008; Brown *et al.* 2009, this issue), although this conclusion is controversial (Rydelek and Horiuchi 2006; Yamada and Ide 2008), and a satisfactory physical explanation remains elusive. It may be sufficient to know that an event is **M** 6.5 or larger and broadcast a warning. However, methodologies to map the finite ruptures of these large (**M** > 7) earthquakes could also be developed and would enhance system performance (Yamada *et al.* 2007; Yamada and Heaton 2008; Zollo *et al.* 2009).

Onsite Warning

The principle of onsite or single-station warning is to detect seismic energy at a single location and provide warning of coming ground shaking at the same location, *i.e.*, detect the *P* wave and predict the peak shaking. This is possible using a combination of the *P*-wave parameters described above. The simplest approach is to look for a scaling relation between the *P*-wave amplitude and the peak ground-shaking (*e.g.*, Wu and Kanamori 2005b). However, small magnitude earthquakes may have very large amplitude but high frequency spikes. Combining the amplitude with frequency information is therefore a more robust approach. If large amplitudes are also associated with low frequencies, *i.e.*, larger magnitudes, then a warning should be issued.

UrEDAS is the grandfather of earthquake early warning systems in general and onsite warning specifically (Nakamura 1988). UrEDAS uses three seconds of the *P* wave to estimate source parameters. Predominant period is used to estimate magnitude, and then the *P*-wave amplitude and magnitude provide an estimate of epicentral distance. The particle motion is used to estimate the event azimuth and depth. All this is achieved with a single three-component seismometer and with remarkable accuracy. The complete point source description can then be used to trigger an onsite alert based on predefined criteria. The Compact UrEDAS uses the same principles but only one second of the *P* wave to provide more rapid warn-

ings (Nakamura and Saita 2007b). UrEDAS continues to be used along the rail systems in Japan (Nakamura 1996, 2004; Nakamura and Saita 2007b) and a mobile unit named FREQL is also in use by emergency response teams (Nakamura and Saita 2007a).

The τ_c–P_d method is another onsite method that combines two of the P-wave parameters described above (Wu and Kanamori 2005a; Wu and Kanamori 2005b; Wu et al. 2007; Wu and Kanamori 2008a, 2008b). When a station triggers on the P-wave arrival, τ_c is used to estimate magnitude and P_d to estimate peak ground velocity (PGV). Through careful selection of the appropriate combinations of τ_c and P_d, as well as through the introduction of station corrections, the system can be tuned to alert only when strong shaking is expected (Böse, Hauksson, Solanki, Kanamori, Wu, and Heaton 2009). This methodology is currently being tested in California (Böse, Hauksson, Solanki, Kanamori, and Heaton2009), Taiwan (Hsiao et al. 2009), Japan, China, and at the Pacific Tsunami Warning Center in Hawaii.

Regional Warning

Regional warning makes use of a seismic network and typically combines many or all of the components described above. Historically, seismic networks have been designed to stream waveform data back to a network processing center, where they are processed to detect, assess, and report on earthquakes. The development of EEW has followed this route, installing new processing modules at the network centers to generate earthquake alerts and then distributing the warning to users. "Onsite" processing algorithms are still used in a network setting to provide the most rapid warnings, *i.e.*, warnings based on a P wave at a single station. In addition, networks also allow data from multiple stations to be combined. This gives more accurate predictions of the distribution of ground shaking across the affected region by providing the earthquake location and reduced uncertainties in earthquake magnitude estimates.

Once a communications network is in use both to collect the seismic data and to give warning to users, the front detection concept also provides for increased warning times. Seismometers close to the epicenter are used to detect the event and assess the hazard, and the communications provide warning to users at greater distances. In the case of large magnitude earthquakes (**M** > 6.5), this approach can provide tens of seconds of warning to areas that can expect damage. But there will also likely be a blind zone around the epicenter where no warning is available. This is due to the time lost transmitting data to a processing center, processing the data, and sending out a warning. A true onsite approach, where a seismometer is installed at the user's location and provides a warning at that location, removes these telemetry delays, but with increased probability of false or missed alarms.

Mexico. The operational network-based warning system in Mexico consists of two components: the SAS system for Mexico City and Guerrero and the SASO system for Oaxaca. The SAS system uses a network of 12 accelerometers along the coast of Guerrero above the subduction zone to provide warning to Mexico City ~320 km to the north (Espinosa-Aranda *et al.* 1995; Espinosa-Aranda *et al.* 2009, this issue). The system 1) integrates energy at each station in a time interval starting at the P-wave arrival and equal to twice the S-minus-P time and 2) measures the growth rate. Empirical scaling relations are used to determine whether the earthquakes are "strong" or "moderate," corresponding approximately to **M** ≥ 6 and 6 > **M** ≥ 5 respectively. When two or more stations report a strong earthquake, a "public" warning is issued; when two or more report a moderate earthquake, a "preventive" warning is issued. Although the system waits until well after the S-wave arrival before issuing any alert, ~60 s warning is still available to Mexico City due to the distance. Ground-shaking is still high in the city, and much stronger than is typically the case at such distances, due to amplification by factors of 100–500 caused by the basin sediments on which the city is built (Suárez *et al.* 2009, this issue).

The SASO system uses a network of 36 seismic stations distributed across Oaxaca. The subduction zone earthquakes are distributed over a wider area than the adjacent Guerrero section of the subduction zone (see Figure 9 in Espinosa-Aranda *et al.* 2009, this issue). Because the distances between the earthquake sources and population centers are shorter, algorithms requiring shorter time-windows of data must be used. Empirical relations use parameters measured in two time windows. During the interval from the P- to the S-arrival, the dominant period, peak acceleration, and energy are measured. When the S-minus-P time is more than three seconds, the dominant period of the first three seconds of the P wave is also measured. These parameters are used to determine whether the earthquake is strong or moderate. Public or preventive warnings are then issued, as with the SAS system.

Japan. The operational warning system implemented by the Japan Meteorological Agency (JMA) combines both an alert-seismograph concept and a network-based approach (Kamigaichi *et al.* 2009, this issue). The system makes use of ~1,000 seismic instruments across Japan, 200 operated by JMA and 800 by the National Research Institute for Earth Science and Disaster Prevention (NIED), and integrates methodologies developed by JMA (Hoshiba *et al.* 2008) and NIED (Nakamura *et al.* 2009). When a single station observes ground-shaking above 100 cm/sec², an alert is triggered (the alert-seismograph approach). In addition, the network approach is used. The source is characterized based on single and multiple P-wave detections. First, the location is estimated. Using a single P-wave detection, the slope of the onset is translated to epicentral distance, and the azimuth is estimated by fitting an ellipsoid to the particle motion (Odaka *et al.* 2003). In addition, when one or two stations have detected a P wave, a "territory" region is defined where the event must have occurred based on the fact that other stations have not yet triggered (Horiuchi *et al.* 2005). The centroid of the territory is used as the epicenter. The depth is fixed at 10 km. Once three or more stations have triggered, a grid search for the optimal

location that minimizes misfit with the observed arrival times is used (Kamigaichi 2004).

The magnitude is estimated using scaling between the *P*-wave amplitude and magnitude, correcting for the epicentral distance. The vector summation of the three-component waveform is monitored continuously and the magnitude estimate updated as the amplitude increases. Once the *S* wave arrives, a new scaling relation is used. Given the location and magnitude, peak ground motion is obtained by estimating the distribution of peak velocity on bedrock, applying site amplification factors, and converting peak velocity to JMA intensity (Kamigaichi 2004), essentially the same approach as is used for ShakeMaps after an earthquake. The system provides an estimate of the intensity and time until shaking for each subprefecture (Kamigaichi *et al*. 2009, this issue).

ElarmS. The ElarmS EEW methodology (http://www.ElarmS.org) is currently being tested statewide on the real-time seismic systems in California (Allen, Brown, Hellweg *et al*. 2009) and has been modified for offline testing using earthquakes from Japan (Brown *et al*. 2009, this issue). The approach processes seismic waveforms individually to generate *P*-wave trigger times, P_d, τ_p^{max}, and signal-to-noise ratios. The peak amplitude every second is also determined. These parameters stream continuously into an event monitor module that associates triggers with detected earthquakes, locates earthquakes based on observed arrival times, estimates the magnitude using P_d and τ_p^{max} relations, and predicts the distribution of ground-shaking using attenuation relations and site corrections. The system updates every second, providing an "AlertMap" of the predicted ground-shaking distribution (Wurman *et al*. 2007). Approximately 600 seismic instruments at ~400 sites currently stream into the system in California. At the time of this writing, the system only provides warning to members of the research group.

Virtual Seismologist. The Virtual Seismologist methodology is also undergoing real-time testing in California, using the same ~600 instruments at ~400 sites (Cua *et al*. 2009, this issue), and in Switzerland. The approach uses the peak acceleration, velocity, and displacement every second to detect earthquakes, locate them, and estimate the magnitude. The methodology uses a Bayesian approach to predict the likelihood of a given magnitude and source location using prior information such as past seismicity and the Gutenburg-Richter relation (Cua and Heaton 2007), though these are not yet incorporated into the current real-time test version of this system. Virtual Seismologist has also developed a sophisticated scheme for filtering false events. At the time of this writing, the system only provides warning to members of the research group.

Presto. This is a probabilistic evolutionary approach to EEW that is currently undergoing real-time testing using the 28-station Irpinia Seismic Network (ISNet) in southern Italy (Weber *et al*. 2007). It uses the *P*-wave arrival times, along with the information that some stations have not yet triggered, to identify the 3D region where the earthquake origin could be located (Satriano *et al*. 2008). The low-frequency amplitude of the *P* wave and also *S* wave is used to estimate magnitude (Lancieri and Zollo 2008). The uncertainty in the EEW alerts has been modeled extensively and shows that the largest source of uncertainty in PGA estimates is the inherent uncertainty in the ground motion prediction equation and not the rapid magnitude and location estimates (Iervolino *et al*. 2009). The performance of the system in large-magnitude events has also been studied and indicates a significant effect of source finiteness (Zollo *et al*. 2009).

PreSEIS. PreSEIS is a neural-network based approach to early warning using *P*-wave arrival times and ground motions at one or more stations to locate earthquake hypocenters, estimate the magnitude and expected ground motions, and predict the final expansion of the evolving seismic rupture for large magnitude earthquakes (Böse *et al*. 2008). In order to train and test the neural networks, the PreSEIS approach has been applied to the station distributions in Istanbul and southern California using synthetic seismograms for finite-fault scenarios (Böse *et al*. 2008) and envelope functions of real earthquakes (Köhler *et al*. 2009, this issue), respectively.

SOSEWIN. The Self-organizing Seismic Early Warning Information Network is a network of 20 stations installed in the Ataköy district of Istanbul in June 2008, which is currently undergoing real-time testing (Fleming *et al*. 2009, this issue). This system is different from those described above in that there is no central network processing center. Instead, each station combines a sensor, onsite processing, and wireless communications to the adjacent stations. Software at each location triggers on seismic arrivals and calculates a range of parameters including arrival time, peak amplitudes, predominant period, etc. Adjacent stations share this information, and alerts can be generated based on a single-station detection, multiple adjacent stations, or multiple components of the array. The current testing is focused on communications, operation reliability, and identifying trigger thresholds. In principle, any of the methodologies described above could be applied to a self-organizing wireless network like this.

Geodetic Networks

Most early warning system development to date has focused on the use of seismological networks. Historically, it is seismic networks that have provided real-time and post-earthquake information, and these networks are very effective at detecting earthquakes, locating earthquakes, and rapidly estimating the magnitude for small and moderate earthquakes. The ability of these *P*-wave-based methods to rapidly and accurately detect large earthquakes ($\mathbf{M} > 7$) is controversial as discussed above. Real-time, high-sample-rate GPS networks are now becoming more prevalent and could provide real-time constraints. The real-time accuracies are currently at the subcentimeter level, meaning that they could provide constraints for large magnitude events.

In this issue, Crowell *et al.* (2009) describe a prototype warning system currently implemented in southern California. GPS data from the California Real Time Network is streamed to the Scripps Orbit and Permanent Array Center, where it is processed using the method of instantaneous positioning (Bock *et al.* 2000). Triangulation is then used to determine the principal components of strain across the network. The current system triggers e-mail alerts when anomalous strain above a predefined threshold occurs. The GPS data can also be used to estimate the earthquake location, and Crowell *et al.* (2009, this issue) are developing scaling relations that could be used to estimate the magnitude.

APPLICATIONS OF EEW

Active warning systems that provide alerts to one or more users have been documented in five countries (Figure 1). Mexico and Japan stand apart as having systems with warnings provided to the general public via multiple communication routes. Taiwan, Turkey, and Romania also have warning systems that provide information to one or more users.

Mexico

The SAS system for Mexico City was developed following the **M** 8.1 earthquake on 19 September 1985, which killed 10,000 and injured 30,000. In August 1991, the system started providing warnings to a small group of users including 25 schools and the subway. In May 1993, it accurately warned of an **M** 6.0 earthquake. The system started providing public warnings to Mexico City in August 1993, making it the first publicly available warning system in the world (Espinosa-Aranda *et al.* 1995). Strong earthquakes generate public warnings distributed through 58 public AM and FM radio stations and six TV channels in Mexico City , plus three radio and one TV station in Toluca (50 km west of Mexico City). In addition, more than 250 users receive both public and preventive warnings through dedicated radio links. These users are mainly primary and secondary schools, universities, emergency and safety agencies, government buildings, civil protection organizations, and the subway system. SAS bulletins are also issued to more than 1,800 users via e-mail and posted on the SAS Web site (Espinosa-Aranda *et al.* 2009, this issue).

From October 1991 to March 2009 the SAS system issued 13 public and 52 preventive warnings. The magnitude of events generating public and preventive warnings ranges from 4.8 to 7.3 and 4.1 to 7.3, respectively. In this issue, Suárez *et al.* (2009) evaluate this performance and conclude that while the SAS system is capable of detecting hazardous earthquakes and providing warning, the accuracy of the magnitude estimates do not warrant the distinction between public and preventive warnings. There have been two missed events with magnitudes of 6.3 and 6.7 and one false alarm on November 16, 1993, when a public warning was issued but there was no earthquake. This false alarm was issued to an estimated radio audience of 2 million people during rush hour, but there are no reports of panic (Espinosa-Aranda *et al.* 1995). The **M** 7.3 earthquake

on 14 September 1995, almost exactly 10 years after the 1985 earthquake that led to the development of the SAS system, was detected and a public warning issued 72 s before the *S*-wave arrival. In this event, the subway was stopped 50 s before the *S*-wave arrival, and schools responded and evacuated as planed (Espinosa-Aranda *et al.* 1995; Goltz and Flores 1997).

The younger SASO system started providing public warning in Oaxaca in 2003. Since that time it has issued three public and five preventive warnings and missed two detections. The SASO system has not been able to maintain continued operations due to funding lapses. Insufficient funding for education and outreach efforts are also cited as a serious problem that will likely result in failure of the system to reduce the impacts of earthquakes on the population (Espinosa-Aranda *et al.* 2009, this issue). There is also concern that the system does not have more users. Only 76 schools out of a possible 5,500 in Mexico City use the system. This is not due to poor, or perceived poor, performance. In a survey, 90% of users rated the service provided as good or very good. Instead, the fact that there has never been a strategy to identify institutions and critical facilities and lifelines that could benefit from the SAS system is considered to be a failure of the overall implementation strategy (Suárez *et al.* 2009, this issue).

Japan

Japan Railways began using alarm-seismometers in the 1960s and then front-detection EEW systems in 1982 to shut off power to the Shinkansen bullet trains. The onsite UrEDAS system started operation along the Shinkansen lines in 1992 and was expanded across the system following the 1995 Kobe earthquake. The Kobe earthquake also motivated a more rapid version called Compact UrEDAS that became operational within rail and metro systems in 1998. It was not until the 2004 **M** 6.6 Niigata Ken Chuetsu earthquake that a major damaging earthquake occurred in Japan during the daytime operations of the Shinkansen. Out of the four trains that were operational in the epicentral region at the time, one derailed. The *P* wave reached the Compact UrEDAS in the section of the derailed train 2.9 s after the origin time and issued an alert one second later, cutting the power supply to the train and initiating braking. The train operator also saw the Compact UrEDAS warning and initiated braking one second after the automated braking. The *S* wave hit the train 2.5 s after the alarm and strong shaking started one second after that (Nakamura and Saita 2007b). While the train derailed, all but one carriage remained on the tracks.

The scale of the 1995 Kobe earthquake damage, which killed more than 6,000 and caused an estimated $U.S. 200 billion in losses, led to the development of a nationwide warning system. Following this event, several nationwide seismic networks were installed with constant station density across the country. These included ~800 high-sensitivity stations (Hi-net) of which ~650 have up- and down-hole strong-motion instruments (KiK-net). An additional ~1,000 surface strong-motion instruments (K-net) and ~70 broadband seismometers (F-net) were installed (Okada *et al.* 2004). These stations were

installed by NIED. JMA had recently completed the renewal of its nationwide seismometer network including ~200 strong-motion meters following the 1993 Okushiri earthquake in order to provide more rapid and accurate tsunami warning and earthquake information. Following the installation of these networks, JMA began testing EEW methodologies in February 2004. During an **M** 7.2 earthquake off the coast of Miyagi Prefecture on 16 August 2005, a warning was generated 4.5 s after the first *P*-wave detection and 16 s before the arrival of the *S* wave at the city of Sendai (Hoshiba *et al.* 2008). JMA started issuing warnings to a limited group of users in August 2006 and began public warnings in October 2007.

During the period of limited warning (August 2006 to October 2007), a public education campaign was enacted by JMA to provide information about the purpose and limitations of EEW and the proper actions to be taken. This included distributing leaflets, short informational videos broadcast on television, posters, conducting seminars, and posting information on the JMA Web site (http://www.jma.go.jp/jma/en/Activities/eew.html). Figure 2 shows the English version of the leaflet describing the actions to be taken in response to an EEW alert.

The now operational public warning system combines the ~800 Hi-net and 200 JMA strong-motion stations to provide a network with a constant 20-km station spacing across the entire country. Warnings are issued to the public when the maximum intensity is predicted to be 5-lower on the JMA scale (~VII–VIII on the Modified Mercalli Intensity scale) or greater. From October 2007 to March 2009, there were 11 earthquakes for which a public warning was issued and/or shaking intensity 5-lower or greater was observed (see Table 1 in Kamigaichi *et al.* 2009, this issue). There were two missed alarms when the maximum predicted intensity was 4 but 5-lower was observed, and three false alarms when intensity 5-lower was predicted but only 4 was observed. The largest event was the onshore 14 June 2008 **M** 7.2 earthquake. The first public warning was issued 4.5 s after the first detection and was updated 18 s later. As expected, there was no warning at the epicenter, but the warnings were available and known to have been used by many people. Some specific reported uses include taking personal protective actions in a nursery, kindergarten, school, home, several offices, and a factory. The warning was used to automatically control elevators and factory systems and issue a "go-around" command to an aircraft on final approach. One driver also reported receiving the warning and stopping without incident. The system also provided warning for the 11 September 2008 **M** 7.1 offshore earthquake, demonstrating that the system is effective for both on- and off-shore events (Kamigaichi *et al.* 2009, this issue). There are no reports of panic during these events and no reports of car accidents.

The public warnings from JMA are communicated to the public via various means. NHK (the Japan Broadcasting Corporation) is required to broadcast the warnings through its nine TV and radio stations. In addition, 122 (out of 127) TV stations and 59 (out of 100) AM/FM radio stations broadcast the warnings as of September 2008. The multihazard J-Alert

system also issues warnings to municipalities. As of March 2009, 226 municipalities (out of 1,851) have J-Alert receivers; 102 use public loud-speaker systems to announce EEW messages. Two cell phone companies provide free warnings to their users and a third is currently developing the capability. An estimated 21 million people can currently receive the warning on their cell phones (Kamigaichi *et al.* 2009, this issue).

In addition to these public warnings, a wide range of users receive the warnings and incorporate them into automated control and response systems. JMA does not provide site-specific warning information but private service-providers can, once certified by JMA. There were 54 certified service-providers as of December 2008. They provide information to 52 out of 204 rail companies (some of which also operate their own EEW systems), factories, construction sites, apartment complexes, schools, shopping malls, hospitals, etc. (Kamigaichi *et al.* 2009, this issue). The Second International Workshop on Earthquake Early Warning held in Kyoto, Japan, in April 2009 provided some specific examples of these systems and their applications as described below.

The private providers offer a variety of services ranging from simple translation of the JMA information into a site-specific predicted intensity and warning time to more sophisticated systems that incorporate local seismometers to provide additional onsite warning. One example is the "home seismometer" (Horiuchi *et al.* 2009), which translates the JMA signal into a site-specific warning and also contains a MEMS sensor that can be used for onsite warning based on *P*-wave detection. The device is mounted on a wall, plugs into AC power and Internet/Ethernet, and issues an audible warning and countdown. About 650 home seismometers are currently deployed across Japan, including ~500 in schools.

One of the home seismometers is installed in the British School in Tokyo and connected to the public address system throughout the school. The students complete three earthquake drills each school year. In the first drill, students are warned when the drill will occur; in the second, they know the week during which it will occur; and the third can be at any time. The school district in Miyagi Prefecture developed and installed its own warning system in the classrooms of four schools. Training programs and videos were prepared and implemented, and the students drill regularly. These drills show that children can get under desks within five seconds in response to an audible warning, and the plan is to expand the system to all schools in the prefecture. While it may take five seconds for students to get under desks, the headmaster of the British School felt that the public address was still important if there was not enough time to take action because it lets student know what is happening and reduces the students' fear. Universities are also installing EEW. For example, at Kogakuin University in Tokyo, elevators currently open at the nearest floor and alert systems are being installed in all the classrooms.

In two earthquakes in 2003 the OKI semiconductor factory in Miyagi Prefecture experienced $U.S. 15 million in losses due to fire, equipment damage, and loss of productivity. Following this experience they spent $U.S. 600,000 installing

At Home

- Protect your head and take shelter under a table
- Don't rush outside
- Don't worry about turning off the gas in the kitchen
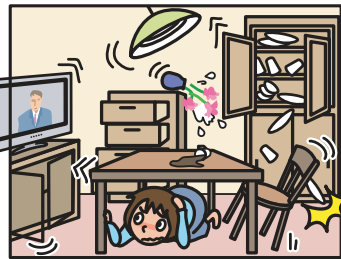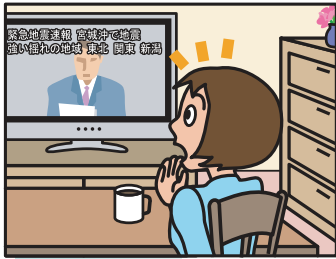
In Public Buildings

- Follow the attendant's instructions
- Remain calm
- Don't rush to the exit

# Earthquake Early Warning: Dos & Don'ts

When Driving

- Don't slow down suddenly
- Turn on your hazard lights to alert other drivers, then slow down smoothly
- If you are still moving when you feel the earthquake, pull over safely and stop

Remain calm, and secure your personal safety based on your surroundings!

After seeing or hearing an Earthquake Early Warning, you have only a matter of seconds before strong tremors arrive. This means you need to act quickly to protect yourself.

Earthquake Early Warning

Outdoors
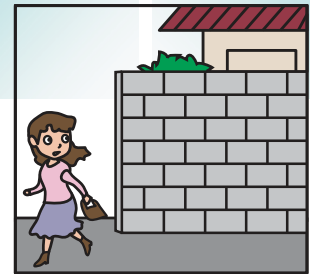
- Look out for collapsing concrete-block walls
- Be careful of falling signs and broken glass
- Take shelter in a sturdy building if there is one close enough

On Buses or Trains
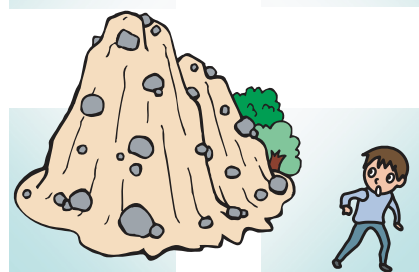
Hold on tight to a strap or a handrail

In Elevators

Stop the elevator at the nearest floor and get off immediately

Near Mountains/Cliffs

Watch out for rockfalls and landslides

▲ **Figure 2**. Informational leaflet prepared by the Japan Meteorological Agency for the public, detailing simple instructions of how to react when they receive an EEW alert. This leaflet and additional information can be found at http://www.jma.go.jp/jma/en/Activities/eew.html.

additional shear walls in the basement and an automated EEW response system that shuts down hazardous chemical systems and moves sensitive equipment to a safe position. In the two earthquakes since the installation, the losses were reduced to $200,000, and the number of days of closure was reduced from 17 and 13 to 4.5 and 3.5, respectively.

Engineering and construction companies are also using the warning systems to provide both enhanced building performance during earthquakes and to protect construction workers. The Kajima Corporation uses the warnings at its facilities. In its office buildings, elevators stop and open at the nearest floor, lights turn on, blinds open, and alerts are issued for personal protective measures. On construction sites, workers move away from or out of hazardous locations. The Shimizu Corporation also provides warning to its offices and construction sites. In addition, they offer a variety of EEW services to their clients following construction. Clients currently using Shimizu's EEW services include a bank, a hotel, and a semiconductor manufacturer.

Istanbul, Taiwan, and Bucharest

Following two **M** 7+ earthquakes in 1999 on the north Anatolian fault to the east of the Marmara Sea, and recognition of the westward migration of earthquakes toward Istanbul, design and installation of EEW for Istanbul was initiated. Two facility-specific EEW systems were initially installed and remain in operation: one for the Iş-Kul high-rise office building and the other for the Enron-Trakya electric power station. A system for the city as a whole was also installed. It consists of 10 strong-motion instruments deployed along the northern shore of the Marmara Sea as part of the Istanbul Earthquake Rapid Response and Early Warning System (Erdik *et al.* 2003). The current system is based on the exceedance of predefined thresholds of ground motions at two to three sensors before a warning is declared (Alcik *et al.* 2009). The system is now operational and expects to start providing warning to several industrial users in 2010. The first users will be Marmara Tube Tunnel beneath the Bosporus Straits (currently under construction), to stop trains entering the tunnel, and the Istanbul Natural Gas Distribution Network, which plans to use the system to actuate shut-off valves. There is also a plan to add seafloor seismometers close to the fault trace to increase warning time.

In the 15 November 1986 **M** 7.8 earthquake offshore Hualien, Taiwan, the most severe damage occurred in Taipei—more than 120 km away—due to basin amplification effects. Since that time, Taiwan has been developing EEW. In 2001, the first EEW system in Taiwan started operation and continues to be used today. It uses ~100 accelerometers deployed across the island and a Virtual Sub-Net (VSN) algorithm to detect and locate earthquakes and estimate magnitudes using the *P*- and *S*-wave energy (Wu and Teng 2002). On average, the system provides warnings 20 s after the origin time, corresponding to when the *S* wave is ~70 km from the epicenter. A second system that uses P_d, τ_c, and τ_p^{max} relations is now being tested to reduce the size of the blind zone. The warnings are not issued to the public, because no public education campaign has been possible; however, warnings have been issued in an experimental mode to railway and rapid transit companies, disaster prevention agencies, and a hospital (Hsiao *et al.* 2009).

The EEW system for Bucharest takes advantage of the highly localized source of large earthquakes in the Romanian Vrancea zone of the southeastern Carpathians. The four strong events (**M** 6.9–7.7) observed during the last century all occurred in the same region at hypocentral distances of ~160 km. A network of three seismic stations in the epicentral Vrancea region is used to detect earthquakes and issue a warning in Bucharest, providing 20–25 sec warning time (Wenzel *et al.* 1999; Böse *et al.* 2007). The system currently gives warning to the Horia Hulubei National Institute of Physics and Nuclear Engineering, where it is used to place a nuclear source in a safe position, and there are plans to provide warning to additional users (Ionescu *et al.* 2007).

PERSPECTIVES, MISCONCEPTIONS, AND CHALLENGES

The last five years have seen rapid and accelerating development of EEW methodologies and implementation around the world. Prior to 2003, the number of EEW manuscripts in the peer-reviewed literature ranged from zero to two per year. The number has been steadily increasing every year since to more than 15 in 2008. This is an indication of the increasing interest in EEW within the seismology and engineering communities, which has resulted in a corresponding increase in the sophistication of available EEW methodologies.

At the same time, significant progress has been made implementing EEW (Figure 1). At the turn of the decade the only EEW systems providing warnings were UrEDAS to rail systems in Japan and the SAS for Mexico City. Today, Japan has nationwide, publicly available EEW (Kamigaichi *et al.* 2009, this issue) and Mexico has expanded its system (Espinosa-Aranda *et al.* 2009, this issue). Taiwan, Istanbul, and Bucharest have active systems providing warning to one or more users (Ionescu *et al.* 2007; Alcik *et al.* 2009; Hsiao *et al.* 2009). All are being continually updated and improved. Real-time testing of EEW is underway on various seismic networks in Italy, Switzerland, China, Hawaii, and California. In California, real-time testing has demonstrated proof-of-concept by generating hazard information before ground-shaking was felt (Allen, Brown, Hellweg *et al.* 2009; Böse, Hauksson, Solanki, Kanamori, and Heaton 2009; Cua *et al.* 2009, this issue).

In 2005, the First International Workshop on Earthquake Early Warning was held at the California Institute of Technology. That meeting focused on the question of whether EEW was scientifically possible. By the time of the Second International Workshop on Earthquake Early Warning held in April 2009 at Kyoto University in Japan, it was clear that the answer is yes. EEW is scientifically and technically possible not just in a front-detection scenario such as Mexico City, but also for earthquake sources much closer to population centers as illustrated in onshore earthquakes in Japan. The question

now is: How useful is this information and how should it be applied?

One common misconception about EEW is that a warning about an imminent earthquake is likely to result in panic. Social scientists have long studied this issue and find that it is not the source of concern many seismologists think it is (*e.g.*, Quarantelli 1956; Goltz 2002). The experience from many public earthquake alerts in Japan and Mexico also provide no evidence suggesting that warnings result in panic. There is no evidence for traffic accidents resulting from warnings, and no evidence of public stampedes. Implementation of EEW does require a broad public education campaign as was carried out in Japan (Kamigaichi *et al.* 2009, this issue). Lack of funding for the necessary education is cited as a problem in Mexico and Taiwan (Hsiao *et al.* 2009; Espinosa-Aranda *et al.* 2009, this issue; Suárez *et al.* 2009, this issue).

Another concern with EEW implementation is that the system will only be used once a decade or less. UrEDAS was installed along the rail systems of Japan in 1992, but there were no earthquakes necessitating activation until 2004 when it did successfully initiate automatic train braking (Nakamura and Saita 2007b). There is no reason why a system cannot activate for smaller, more frequent earthquakes. These warnings could still be provided to appropriate users for informational purposes, offering an end-to-end test of the EEW system. Informational alerts used in an appropriate fashion can remind people of the earthquake hazard and also be turned into an opportunity for education and increased preparedness generally.

The most important scientific challenge that would have the potential to significantly improve EEW systems is the recognition and real-time mapping of finite-fault sources. None of the active EEW systems currently identify source finiteness. There has been much discussion in the literature about saturation of the *P*-wave parameters used to estimate magnitude for large ($\mathbf{M} > 7$) earthquakes (*e.g.*, Olson and Allen 2005; Rydelek and Horiuchi 2006; Zollo *et al.* 2006; Lewis and Ben-Zion 2008; Yamada and Ide 2008; Murphy and Nielsen 2009; Brown *et al.* 2009, this issue). But this uncertainty in the magnitude estimate for large earthquakes is probably not the greatest source of uncertainty in ground-shaking predictions. For moderate earthquakes, it is clear that the largest source of uncertainty lies in the ground-motion prediction equations, not the rapid event magnitude and location estimates generated by EEW systems (Iervolino *et al.* 2009; Brown *et al.* 2009, this issue). Even with accurate magnitude estimates for large earthquakes, the orientation and lateral extent of the fault rupture have a profound effect on the distribution of ground-shaking. One approach is to simply warn an entire region when an $\mathbf{M} > 6.5$ earthquake is detected. Although only some areas within the region would experience extreme shaking and others would only feel moderate shaking, most users would not consider this a false alarm. Still, EEW performance could be enhanced both in accuracy and warning times by integrating finite source detection methods (Heaton 1985; Allen 2006). Research is already underway using seismic methods to detect fault finiteness by assessing the proximity of stations to the fault and to map slip on the fault in real time (Yamada *et al.* 2007; Yamada and Heaton 2008; Zollo *et al.* 2009). Real-time geodetic data can currently offer accuracies at the subcentimeter level and could therefore provide constraints on these large-magnitude events as well (Crowell *et al.* 2009, this issue). Much more could be done using both seismic and geodetic data, integrating their complementary constraints, and also integrating *a priori* constraints such as fault models and rupture physics.

Each of the active EEW systems has been implemented in response to a significant damaging earthquake. The challenge for earthquake-prone regions without EEW is to implement a system before the next big earthquake rather than following it. To this end, outreach and education of EEW capabilities beyond the seismology community is important. There are indications of success toward this end. In Italy, ISNet has been installed and is currently testing EEW in response to a known earthquake threat. In California, legislation is currently pending to investigate the integration of EEW within a new high-speed rail link. This may be one step toward a public EEW system for the state and the United States. This special issue of *Seismological Research Letters* facilitates the open exchange of information regarding early warning methodologies and their implementation. Our hope is that this exchange of information can be used to promote the appropriate application of EEW systems.

ACKNOWLEDGMENTS

REFERENCES

Alcik, H., O. Ozel, N. Apaydin, and M. Erdik (2009). A study on warning algorithms for Istanbul earthquake early warning system. *Geophysical Research Letters* **36**, L00B05; doi:10.1029/2008GL036659.

Allen, R. M., and H. Kanamori (2003). The potential for earthquake early warning in southern California. *Science* **300**, 786–789.

Allen, R. M. (2006). Probabilistic warning times for earthquake ground shaking in the San Francisco Bay Area. *Seismological Research Letters* **77**, 371–376.

Allen, R. M., H. Brown, M. Hellweg, O. Khainovski, P. Lombard, and D. Neuhauser (2009). Real-time earthquake detection and hazard assessment by ElarmS across California. *Geophysical Research Letters* **36**, L00B08; doi:10.1029/2008GL036766.

Allen, R. M., P. Gasparini, and O. Kamigaichi, eds. (2009). New methods and applications of earthquake early warning. *Geophysical Research Letters* **36**, L00B05, L00B08, L00B03, L00B04, L00B02, L00B06, L00B01, L00B07.

Bock, Y., R. Nikolaidis, P. J. De Jonge, and M. Bevis (2000). Instantaneous geodetic positioning at medium distances with the Global Positioning System. *Journal of Geophysical Research* **105**, 28,233–28,253.

Bock, Y., B. Crowell, F. Webb, S. Kedar, R. Clayton, and B. Miyahara (2008). Fusion of high-rate GPS and seismic data: Applications to early warning systems for mitigation of geological hazards. *Eos, Transactions, American Geophysical Union* **89**, G43B-01.

Böse, M., C. Ionescu, and F. Wenzel (2007). Earthquake early warning for Bucharest, Romania: Novel and revisited scaling relations. *Geophysical Research Letters* **34**, L07302.

Böse, M., F. Wenzel, and M. Erdik (2008). PreSEIS: A neural network-based approach to earthquake early warning for finite faults. *Bulletin of the Seismological Society of America* **98**, 366–382.

Böse, M., E. Hauksson, K. Solanki, H. Kanamori, and T. H. Heaton (2009). Real-time testing of the on-site warning algorithm in southern California and its performance during the July 29, 2008 *Mw* 5.4 Chino Hills earthquake. *Geophysical Research Letters* **36**, L00B03; doi:10.1029/2008GL036366.

Böse, M., E. Hauksson, K. Solanki, H. Kanamori, Y.-M. Wu, and T. Heaton (2009). A new trigger criterion for improved real-time performance of on-site early warning in southern California. *Bulletin of the Seismological Society of America* **99**, 897–905.

Brown, H., R. M. Allen, and V. F. Grasso (2009). Testing ElarmS in Japan. *Seismological Research Letters* **80** (5), 727–739.

Cooper, J. D. (1868). Earthquake indicator. *San Francisco Bulletin*, November 3, 1868.

Crowell, B. W., Y. Bock, and M. B. Squibb (2009). Demonstration of earthquake early warning using total displacement waveforms from real-time GPS networks. *Seismological Research Letters* **80** (5), 772–782.

Cua, G., and T. Heaton (2007). The Virtual Seismologist (VS) method: A Bayesian approach to earthquake early warning. In *Earthquake Early Warning Systems*, ed. P. Gasparini, G. Manfredi, and J. Zschau, 97–132. Berlin and Heidelberg: Springer.

Cua, G., M. Fischer, T. Heaton, and S. Wiemer (2009). Real-time performance of the Virtual Seismologist earthquake early warning algorithm in southern California. *Seismological Research Letters* **80** (5), 740–747.

Erdik, M., Y. Fahjan, O. Ozel, H. Alcik, A. Mert, and M. Gul (2003). Istanbul earthquake rapid response and early warning system. *Bulletin of Earthquake Engineering* **1**, 157–163.

Espinosa-Aranda, J. M., A. Jimenez, G. Ibarrola, F. Alcantar, A. Aguilar, M. Inostroza, and S. Maldonado (1995). Mexico City Seismic Alert System. *Seismological Research Letters* **66**, 42–52.

Espinosa-Aranda, J. M., A. Cuellar, A. Garcia, G. Ibarrola, R. Islas, S. Maldonado, and F. H. Rodriguez (2009). Evolution of the Mexican Seismic Alert System (SASMEX). *Seismological Research Letters* **80** (5), 694–706.

Fleming, K., M. Picozzi, C. Milkereit, F. Kühnlenz, B. Lichtblau, J. Fischer, C. Zulfikar, O. Ozel, and the SAFER and EDIM Working Groups (2009). The Self-organizing Seismic Early Warning Information Network (SOSEWIN). *Seismological Research Letters* **80** (5), 755–771.

Goltz, J. D., and P. J. Flores (1997). Real-time earthquake early warning and public policy: A report on Mexico City's Sistema de Alerta Sismica. *Seismological Research Letters* **68**, 727–733.

Goltz, J. D. (2002). Introducing earthquake early warning in California: A summary of social science and public policy issues. Sacramento California: Governor's Office of Emergency Services (June).

Heaton, T. H. (1985). A model for a seismic computerized alert network. *Science* **228**, 987–990.

Horiuchi, S., H. Negishi, K. Abe, A. Kamimura, and Y. Fujinawa (2005). An automatic processing system for broadcasting earthquake alarms. *Bulletin of the Seismological Society of America* **95**, 708–718.

Horiuchi, S., Y. Horiuchi, S. Yamamoto, H. Nakajima, C. Wu, P. A. Rydelek, and M. Kachi (2009). Home seismometer for earthquake early warning. *Geophysical Research Letters* **36**, L00B04.

Hoshiba, M., O. Kamigaichi, M. Saito, S. Tsukada, and N. Hamada (2008). Earthquake early warning starts nationwide in Japan. *Eos, Transactions, American Geophysical Union* **89**, 73–80.

Hsiao, N.-C., Y.-M. Wu, T.-C. Shin, L. Zhao, and T.-L. Teng (2009). Development of earthquake early warning system in Taiwan. *Geophysical Research Letters* **36**, L00B02.

Iervolino, I., M. Giorgio, C. Galasso, and G. Manfredi (2009). Uncertainty in early warning predictions of engineering ground motion parameters: What really matters? *Geophysical Research Letters* **36**, L00B06.

Ionescu, C., M. Böse, F. Wenzel, A. Marmureanu, A. Grigore, and G. Marmureanu (2007). An early warning system for deep Vrancea (Romania) earthquakes. In *Earthquake Early Warning Systems*, ed. P. Gasparini, G. Manfredi, and J. Zschau, 343–349. Berlin and Heidelberg: Springer.

Kamigaichi, O. (2004). JMA earthquake early warning. *Journal of the Japan Association for Earthquake Engineering* **4**, 134–137.

Kamigaichi, O., M. Saito, K. Doi, T. Matsumori, S. Tsukada, K. Takeda, T. Shimoyama, K. Nakamura, M. Kiyomoto, and Y. Watanabe (2009). Earthquake early warning in Japan: Warning the general public and future prospects. *Seismological Research Letters* **80** (5), 717–726.

Kanamori, H. (2005). Real-time seismology and earthquake damage mitigation. *Annual Review of Earth and Planetary Sciences* **33**, 195–214.

Köhler, N., G. Cua, F. Wenzel, and M. Böse (2009). Rapid source parameter estimations of southern California earthquakes using PreSEIS. *Seismological Research Letters* **80** (5), 748–754.

Lancieri, M., and A. Zollo (2008). A Bayesian approach to the real-time estimation of magnitude from the early *P* and *S* wave displacement peaks. *Journal of Geophysical Research* **113**, B12302, doi:10.1029/2007JB005386.

Lewis, M. A., and Y. Ben-Zion (2008). Examination of scaling between earthquake magnitude and proposed early signals in *P* waveforms from very near source stations in a South African gold mine. *Journal of Geophysical Research* **113**, B09305, doi:10.1029/2007JB005506.

Lockman, A., and R. M. Allen (2007). Magnitude-period scaling relations for Japan and the Pacific Northwest: Implications for earthquake early warning. *Bulletin of the Seismological Society of America* **97**, 140–150.

Murphy, S., and S. Nielsen (2009). Estimating earthquake magnitude with early arrivals: A test using dynamic and kinematic models. *Bulletin of the Seismological Society of America* **99**, 1–23.

Nakamura, H., S. Horiuchi, C. Wu, S. Yamamoto, and P. A. Rydelek (2009). Evaluation of the real-time earthquake information system in Japan. *Geophysical Research Letters* **36**, L00B01.

Nakamura, Y. (1984). Development of earthquake early-warning system for the Shinkansen, some recent earthquake engineering research and practice in Japan. *Proceeding of The Japanese National Committee of the International Association for Earthquake Engineering*, June 1984, 224–238.

Nakamura, Y. (1988). On the urgent earthquake detection and alarm system (UrEDAS). In *Proceedings of the 9th World Conference on Earthquake Engineering* **VII**, 673–678.

Nakamura, Y. (1996). Real-time information systems for hazards mitigation. In *Proceedings of the 11th World Conference on Earthquake Engineering*, paper no. 2134.

Nakamura, Y. (2004). UrEDAS, urgent earthquake detection and alarm system, now and future. In *Proceedings of the 13th World Conference on Earthquake Engineering*, August 2004, paper no. 908.

Nakamura, Y., and J. Saita (2007a). FREQL and AcCo for a quick response to earthquakes. In *Earthquake Early Warning Systems*, ed. P. Gasparini, G. Manfredi, and J. Zschau, 307–324. Berlin and Heidelberg: Springer.

Nakamura, Y., and J. Saita (2007b). UrEDAS, the earthquake warning system: Today and tomorrow. In *Earthquake Early Warning Systems*, ed. P. Gasparini, G. Manfredi, and J. Zschau, 249–282, Berlin and Heidelberg: Springer.

Odaka, T., K. Ashiya, S. Tsukada, S. Sato, K. Ohtake, and D. Nozaka (2003). A new method of quickly estimating epicentral distance and magnitude from a single seismic record. *Bulletin of the Seismological Society of America* **93**, 526–532.

Okada, Y., K. Kasahara, S. Hori, K. Obara, S. Sekiguchi, H. Fujiwara, and A. Yamamoto (2004). Recent progress of seismic observation networks in Japan—Hi-net, F-net, K-NET, KiK-net. *Earth, Planets, and Space* **56**, xv–xxviii.

Olson, E., and R. M. Allen (2005). The deterministic nature of earthquake rupture. *Nature* **438**, 212–215.

Quarantelli, H. (1956). *The Condition of Panic*. Chicago: University of Chicago Press.

Rydelek, P., and S. Horiuchi (2006). Is earthquake rupture deterministic? *Nature* **442**, E5–E6.

Satriano, C., A. Lomax, and A. Zollo (2008). Real-time evolutionary earthquake location for seismic early warning. *Bulletin of the Seismological Society of America* **98**, 1,482–1,494.

Shieh, J. T., Y.-M. Wu, and R. M. Allen (2008). A comparison of tau-c and tau-p-max for magnitude estimation in earthquake early warning. *Geophysical Research Letters* **35**, L20301.

Suárez, G., D. Novelo, and E. Mansilla (2009). Performance evaluation of the seismic alert system (SAS) in Mexico City: A seismological and a social perspective. *Seismological Research Letters* **80** (5), 707–714.

Tsang, L., R. M. Allen, and G. Wurman (2007). Magnitude scaling relations from *P* waves in southern California. *Geophysical Research Letters* **34**, L19304.

Weber, E., G. Iannaccone, A. Zollo, A. Bobbio, L. Cantore, M. Corciulo, V. Convertito, M. Di Crosta, L. Elia, A. Emolo, C. Martino, A. Romeo, and C. Satriano (2007). Development and testing of an advanced monitoring infrastructure (ISNET) for seismic early warning applications in the Campania region of southern Italy. In *Earthquake Early Warning Systems*, ed. P. Gasparini, G. Manfredi, and J. Zschau, 325–341. Berlin and Heidelberg: Springer.

Wenzel, F., M. Onescu, M. Baur, and F. Fiedrich (1999). An early warning system for Bucharest. *Seismological Research Letters* **70**, 161–169.

Wolfe, C. J. (2006). On the properties of predominant period estimators for earthquake early warning. *Bulletin of the Seismological Society of America* **96**, 1,961–1,965.

Wu, Y.-M., and T.-L. Teng (2002). A virtual subnetwork approach to earthquake early warning. *Bulletin of the Seismological Society of America* **92**, 2,008–2,018.

Wu, Y.-M., and H. Kanamori (2005a). Experiment on an onsite early warning method for the Taiwan early warning system. *Bulletin of the Seismological Society of America* **95**, 347–353.

Wu, Y.-M., and H. Kanamori (2005b). Rapid assessment of damage potential of earthquakes in Taiwan from the beginning of *P* waves. *Bulletin of the Seismological Society of America* **95**, 1,181–1,185.

Wu, Y.-M., H. Kanamori, R. M. Allen, and E. Hauksson (2007). Experiment using the tau-c and *Pd* method for earthquake early warning in southern California. *Geophysical Journal International* **170**, 711–717.

Wu, Y.-M., and H. Kanamori (2008a). Development of an earthquake early warning system using real-time strong motion signals. *Sensors* **8**, 1–9.

Wu, Y.-M., and H. Kanamori (2008b). Exploring the feasibility of onsite earthquake early warning using close-in records of the 2007 Noto Hanto earthquake. *Earth, Planets, and Space* **60**, 155–160.

Wurman, G., R. M. Allen, and P. Lombard (2007). Toward earthquake early warning in northern California. *Journal of Geophysical Research* **112**, B08311, doi:10.1029/2006JB004830.

Yamada, M., T. Heaton, and J. Beck (2007). Real-time estimation of fault rupture extent using near-source versus far-source classification. *Bulletin of the Seismological Society of America* **97**, 1,890–1,910.

Yamada, M., and T. Heaton (2008). Real-time estimation of fault rupture extent using envelopes of acceleration. *Bulletin of the Seismological Society of America* **98**, 607–619.

Yamada, T., and S. Ide (2008). Limitation of the predominant-period estimator for earthquake early warning and the initial rupture of earthquakes. *Bulletin of the Seismological Society of America* **98**, 2,739–2,745.

Zollo, A., M. Lancieri, and S. Nielsen (2006). Earthquake magnitude estimation from peak amplitudes of very early seismic signals on strong motion records. *Geophysical Research Letters* **33**, L23312.

Zollo, A., G. Iannaccone, M. Lancieri, L. Cantore, V. Convertito, A. Emolo, G. Festa, F. Gallovic, M. Vassallo, C. Martino, C. Satriano, and P. Gasparini (2009). Earthquake early warning system in southern Italy: Methodologies and performance evaluation. *Geophysical Research Letters* **36**, L00B07.

Dept. of Earth and Planetary Science
University of California, Berkeley
307 McCone Hall
Berkeley, California 94720 U.S.A.
rallen@berkeley.edu
(R. A.)