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Brief communication: Appropriate messaging is critical for effective earthquake early warning systems

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Abstract. The earthquake early warning systems (EEWSs) in China have achieved great progress, with warning alerts being successfully delivered to the public in some regions. We examined the performance of the EEWS in China's Sichuan Province during the 2019 Changning Earthquake. Although its technical effectiveness was tested with the first alert released 10 s after the earthquake, we found that a big gap existed between the EEWS's message and the public's response. We highlight the importance of EEWS alert effectiveness and public participation for long-term resiliency, such as delivering useful alert messages through appropriate communication channels and training people to understand and properly respond.

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1 Why are earthquake early warnings important?

An earthquake is an intense shaking of the Earth's surface, caused by the sudden movement of a plate in the Earth's crust. Destructive earthquakes, such as the 2008 Wenchuan Earthquake (M_w 7.9) in China, the 2010 Haiti Earthquake (M_w 7.0), and the 2011 Tohoku-Oki Earthquake (M_w 9.0) in Japan, trigger multiple secondary hazards (e.g., landslides, tsunamis, and Natech disasters). These earthquakes cause millions of deaths, widespread property damage to buildings and infrastructure, and severe regional economic fallout. Earthquakes are impossible to avoid, and predicting their occurrence remains difficult, so more and more countries have focused on developing earthquake early warning (EEW) and emergency management systems.

An EEW is the detection and characterization of earthquakes as they occur with rapid delivery of alerts to areas potentially affected before the strongest shaking begins (Allen and Melgar, 2019). Because most of an earthquake's energy is carried by the damaging S-and surface waves, which arrive after the faster and lower amplitude P-waves, EEW are possible because both travel far slower than the electromagnetic waves used to transfer information (Cremen and Galasso, 2020). Although the potential warning time may only be seconds to minutes, this time is precious so that individuals and institutions (e.g., airports, trains, manufacturing, and energy facilities) can take action to save lives and mitigate the potential damage from earthquakes (Strauss and Allen, 2016).

2 EEW systems and their applications

Generally, EEW systems (EEWSs) are real-time information systems that consist of three modules, including: 1) monitoring and detecting earthquakes based on seismic networks; 2) EEW processes, e.g., estimation of location, magnitude, maximum seismic intensity, and earliest arrival time, as well as alert notification decisions; and 3) information delivery (Cremen and Galasso, 2020). The importance of EEWSs for disaster mitigation has been widely studied. Many jurisdictions have operational systems to deliver alerts to the general public (e.g., Mexico, Japan, and South Korea), or target specific stakeholders in limited areas (e.g., United States, Turkey, Romania, and India) (Allen and Melgar, 2019, and references therein). There are also some EEWSs in the preparation and testing stages, including in Switzerland, Italy, Mainland China, Nicaragua, and Chile (Allen and Melgar, 2019, and references therein).

Although the theory of EEWSs is simple, the implementation is much more complicated (Allen and Melgar, 2019). An effective EEWS must accurately provide estimated earthquake parameters with long enough warning time to be of practical use for recipients. Therefore, most research over the last three decades has focused on evaluating the systems and optimizing their algorithms with the goal of enhancing the quality and accuracy of EEWs. However, several technical challenges are revealed by reviewing the EEWS development (Allen et al., 2009; Allen and Melgar, 2019; Cremen and Galasso, 2020;

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Hoshiba and Ozaki, 2014; Kamigaichi et al., 2009). For example, 1) it is hard to provide timely warnings in areas closest to epicentres (e.g., the blind zones); 2) when more than two earthquakes occur in close temporal or spatial proximity, the estimation parameters become hard to process and the error substantially increases; 3) The unsaturated magnitude and seismic intensity of large earthquakes (M>8) may be underestimated, such as the Tohoku-Oki Earthquake (Hoshiba and Ozaki, 2014); and 4) The EEWSs may not work properly due to power failures, wiring disconnects, and high background noise caused by large earthquakes and their aftershocks.

Recently, more and more scholars have devoted attention to increasing the effectiveness of EEWS by social means (e.g., Santos-Reyes, 2019; Sutton et al., 2020), which can alleviate the limitations that are difficult to solve with technical innovations. For example, the Japan's EEWS has significantly contributed to reducing social vulnerability to earthquakes through nationwide participation. Most of the alerted respondents can understand and act to protect themselves due to their education and training, although the magnitude of the 2011 Tohoku-Oki Earthquake was under-estimated due to technical limitations, resulting in poor-quality alerts (Fujinawa and Noda, 2013; Hoshiba and Ozaki, 2014). In addition, the United States' EEWS (ShakeAlert) enables recipients to immediately participate in the alert process and define the system capability to enhance public participation, which is currently being tested in California, Oregon, and Washington states (Allen and Melgar, 2019). Comparatively, Mexico's EEWS detected and issued warnings for the 2017 Puebla Earthquake; however, the public took a negative attitude towards its performance since they received little information for either the EEWS or the warnings themselves and had not been previously educated how to act during an emergency response (Santos-Reyes, 2019). These events demonstrate that importance of EEWSs, but also show the critical importance of public awareness education and training, to activate the benefits of EEWSs.

3 China's EEWS Development

The China's EEWS development is particularly challenging because several regions are prone to earthquakes, including major metropolitan areas. Therefore, following the 2008 Wenchuan Earthquake, China's central government encouraged the establishment of a national EEWS, initially focusing efforts on four seismic regions for pilot testing (**Fig. 1a**). With support from the "National System for Fast Seismic Intensity Reporting and Earthquake Early Warning Project" led by the China Earthquake Administration (CEA), a high-quality national seismological network was installed with 15,000 seismic monitoring stations. The instruments aimed at quickly reporting earthquake intensities and earthquake early warnings in key areas on the minute and second scales, respectively. EEWSs in the pilot regions (e.g., Fujian and Sichuan provinces, Lanzhou City, and the Beijing capital region) are now operational and have proven effective to some degree regarding the techniques (e.g., algorithms, software). Detailed descriptions can be found in Peng et al. (2011), Peng et al. (2020), and Zhang et al. (2016), but few of these studies have focused on the information dissemination mechanisms and public response to EEWS.

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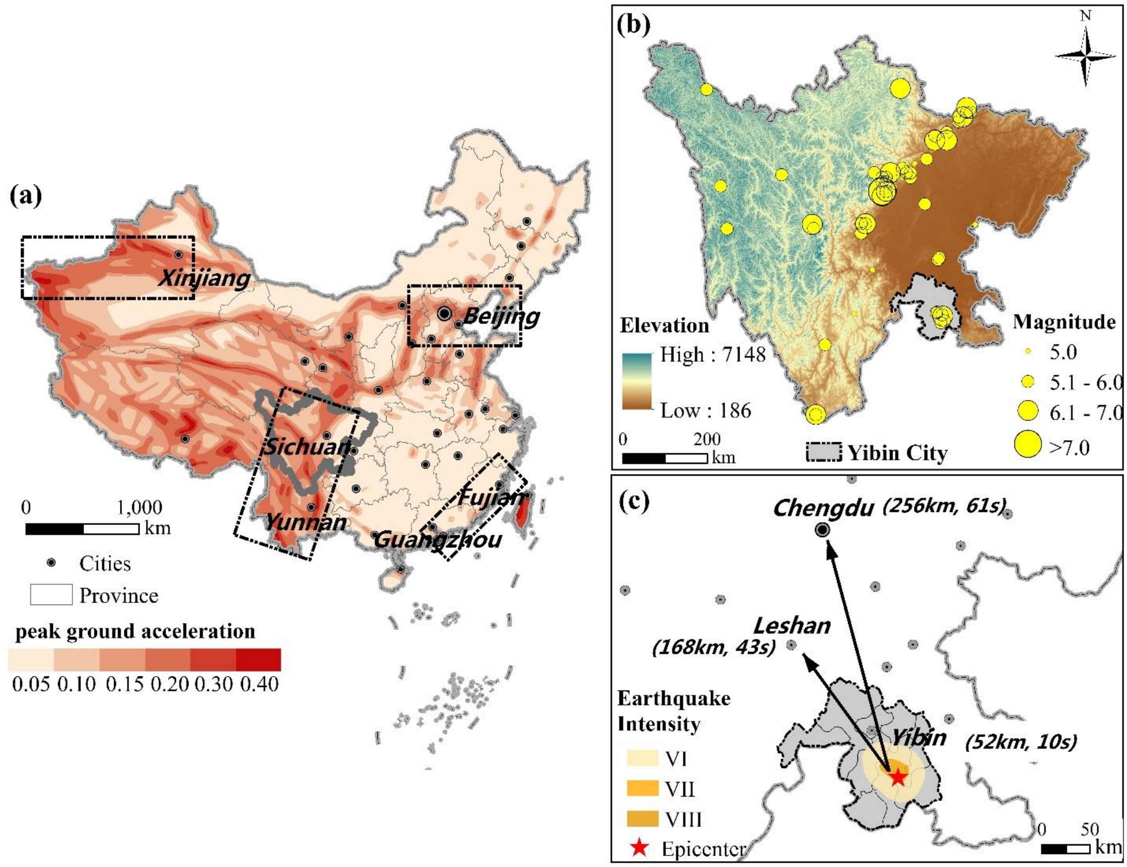

Figure 1 Seismic activity across China. (a) Distribution of installed earthquake intensity and early warning systems in various Chinese regions; (b) historical earthquakes (January 1949-August 2020) in Sichuan Province; and (c) location of the Changning Earthquake. Note: China's four primary seismic regions demarcated by rectangles are (clockwise from top-right): Beijing capital region, southeastern coastal region, central China north-south seismic belt, and northern Xinjiang region. (a) modified from seismic peak ground acceleration zonation map of China (Standardization Administration of the People's Republic of China, 2015).

3.2 Sichuan case

Sichuan is a major earthquake-prone region with 73 earthquakes having magnitudes above Ms 5.0 occurring since the 2008 Wenchuan Earthquake (**Fig. 1b**), based on China Earthquake Networks Center (CENC, http://www.ceic.ac.cn/history). Differing from the one conducted by CEA, Sichuan's EEWS was first built in 2010 and operated by a third-party (Institute of Care-Life, ICL) in collaboration with the Emergency Management Bureau (at the city and county level) (Wang and Lin, 2020). The recent Ms 6.0 Changning Earthquake happened at 22:55 PM on 17th June 2019 in southeast Sichuan's Yibin Municipality, triggering an alert in some cities across the province, including Yibin (52 km from epicenter), Leshan (168 km), and Chengdu (245 km) (**Fig. 1c**). The alerts were issued approximately 10 s, 43 s, and 61 s prior to major shaking in the

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above cities, respectively. It was the first time that an alert system was triggered in Sichuan, which generated great public interest and confusion.

In Chengdu, the provincial capital city, the alert was delivered in several ways, including broadcast sirens, as well as text messages on televisions and cell phones that had special applications installed. Of these, the broadcast siren notified the most people with speakers located in more than 110 residential areas. The alert began with a countdown, followed by loud alarm sirens. However, few people understood what the siren pertained to or what was about to happen with only a countdown and then siren. Only when the shaking began, did most people realize the alarm was intended to warn of an impending earthquake. Most people reported that when the countdown over broadcast speakers began followed by the siren, they were confused and unsure what to do. They did not know what was happening or what would happen, because the countdown and siren were unaccompanied by clear audio messages with explanatory information. Many people interpreted the alarm as a firemen's duty task, an air raid alert test, an explosion, theft alarm from a car or electric bicycle, or a special sales event. Clearly, due to the diversity of reactions, the alert caused more confusion, fear, and disturbance than what was intended by EEWS. Some people were less concerned with the earthquake than by the confusion over the loud countdown and siren, as it was nearly midnight.

We examined the public perception of Sichuan's EEWS using an internet-based survey, conducted June 21-23 in Chengdu with 770 participants. The demographics of the survey participants can be found in Table 1. The participants can be divided into two groups: 1) those who heard the broadcast siren alert (Group A, n=261) and 2) those who did not (Group B, n=509) (**Fig. 2**). We found that large majorities of both groups (Group A, 72%; Group B, 61%) did not understand the purpose of the alert. There were only 55 (21%) from Group A who understood the alert and knew what actions to take. Of these, their knowledge came from previous training (26), hearing a brief note at the beginning of the alert (11), advice from people nearby when the alert was ongoing (7), or other reasons (11). Because so few people knew what the alert was about or recognized what would happen, most people did not have sufficient knowledge or awareness of the correct actions to take. Consequently, this alert could have caused additional problems, including injuries or cardiovascular problems due to fear or panic as people hardly hear such high-decibel blaring sirens by loudspeakers, and the lack of understanding could have led to more acute harm if the shaking level had been higher.

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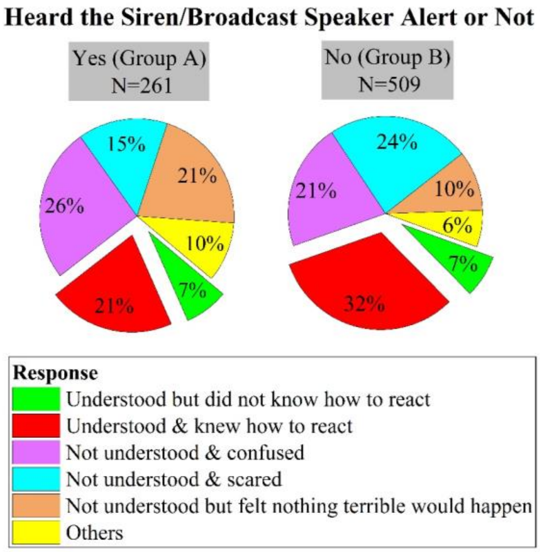

Figure 2 Public responses to the siren/broadcast speaker from an internet-based survey in Chengdu, China. Group A participants heard the siren/broadcast speaker alert on June 17th and Group B did not.

Table 1 Demographic profile of the survey participants (N=770)

Variable		N	%
Gender	Male	220	28.6
	Female	550	71.4
Age	≤18	5	0.6
	19-30	204	26.5
	31-40	326	42.3
	41-60	165	21.4
	>60	70	9.1
Education level	Primary or below	54	7.0
	High school	43	5.6
	Undergraduate	491	63.8
	Postgraduate	182	23.6
Occupation	Students, educational employees, and academics	167	21.7
	Governmental organizations	58	7.5
	Emergency institutions and companies	97	12.6
	Private business, farmers, and	330	42.9
	Other	118	15.3
Earthquake training and education	Yes	518	67.3
	No	252	32.7

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Note: The category of emergency institutions and companies refer to those that typically require the earthquake alerts, such as hospital, train and subway, and factories with hazardous environment. The category of "others" included those that were with no formal jobs and retirees.

4 EEWS Limitations and Implications from Sichuan

The Changning Earthquake's example highlights some challenges with Sichuan's EEWS. We are not arguing against issuing earthquake alerts, however, this event and the resulting confusion raises four important issues that should be addressed moving forward:

First, a big gap exists between the intention of EEWS and its reality in Sichuan. An effective EEWS should be sufficiently tested and publicized widely (Kamigaichi et al., 2009), so that when an alert is issued people understand its meaning and have enough time to take appropriate actions. When installed in a residential area, inhabitants should be notified about the system, and most importantly, informed about what actions they should take after receiving an alert, but before shaking begins. In the case of the EEWS's alert in Chengdu following the Changning Earthquake, inadequate efforts had been made to adequately inform the public prior to the earthquake, so few people were able to understand or respond appropriately to the alert. The experience of leading countries like Japan shows that public training, education, and widespread awareness campaigns about EEWS are the key factors of their success (e.g., Fujinawa and Noda, 2013; Kamigaichi et al., 2009)

Second, of vital importance is what and how to deliver actionable warnings to the public. An effective early alert should not only inform the public about hazards, but also protective actions (Allen and Melgar, 2019; Sutton et al., 2020). The default messages must be simple, because the content and comprehension of EEW messages should result in people taking appropriate actions (Allen and Melgar, 2019; Becker et al., 2020; Santos-Reyes, 2019). Documented messages can be instructions (e.g., Drop, cover, and hold on; US), origin time, and names of epicenter regions and subprefecture areas (e.g., Earthquake early warning. An earthquake has occurred in Area X. Please prepare for strong temblor; Japan) (Kamigaichi et al., 2009; Allen and Melgar, 2019). Providing information about expected shaking intensity or arrival time (countdown) are not recommended, as these can lead to unnecessary panic (Allen and Melgar, 2019; Kamigaichi et al., 2009), but some studies hold the opposite viewpoint (Santos-Reyes, 2019). Furthermore, the information and alerts should be delivered in stable, useful, and suitable ways. As our case study shows, some claimed that the earthquake itself did not scare them as much as the blaring siren did. It seemed unnecessary to use sirens on loudspeakers that day. While the advantage of using sirens is that it rapidly reaches people simultaneously, the use of such "shocking" alarms is needed only with high risks and likelihood of considerable damage. For those that may not lead to causalities or considerable social or economic losses, use of more "gentle" alert channels are recommended. Alerts delivered over the radio, TV, SMS messages, emails, and smartphone applications have shown greater effectiveness in documented cases (Hoshiba and Ozaki, 2014).

Third, at what level the alert should be triggered is a key issue. It is essential to avoid the fabled "boy crying wolf" or over-alerting, which can lead to public frustration and apathy, so alert messages should not be issued unless the shaking is expected to cause considerable damage. The Changning Earthquake did not cause strong motion or significant damage in Chengdu, but 15% and 24% of the participants from Groups A and B[1] were terrified by the alarm sound, respectively. There

[1] Although participants in Group B had not heard the sirens on the day of the earthquake, both groups were shown a video of the siren/alert at the time of the survey.

were no specific criteria for when to issue EEW alarms at that time. The provincial standard was only issued in April 2019, so it had not yet been formally implemented. According to this standard (draft version) [2], a warning should only be issued (to the general public) when the seismic intensity is expected to be VI on the Chinese scale. However, despite the higher level in Yibin, the seismic intensity in Chengdu was lower than VI (**Fig. 1c**), so the alerts should not have been issued in Chengdu. In addition, there continues to be insufficient guidance about how to handle false alarms, updates, and canceled warnings.

Fourth, earthquake alerts should be released by an authoritative government agency. The public should be informed that only alerts from the authorized body are reliable. But it was unclear who was the authority that released the alert on June 17, 2019. There can be many third-party warning service providers, who forward EEW messages by multiple transmission routes. Yet, according to Sichuan's draft standard, the publishing body should only be the Provincial Earthquake Warning Release Center. In addition, the Sichuan case shows that one region may have multiple EEWSs (Wang and Lin, 2020), which will raise greater challenges regarding best practices for issuing EEW and popularizing how to interpret them. Therefore, greater supervision and management systems are urgently needed in Sichuan's EEW practice.

The most important component of a successful EEWS is a group of users who want alerts and can define the necessary capabilities of the system, and next is the physical infrastructure and sensor system (Allen and Melgar, 2019). The Changning Earthquake warning event showed that the transmission and utilization of EEW lagged behind the technological development and physical construction. The public in affected areas were not well-informed by EEWS alerts, nor were they adequately trained on how to respond. Therefore, we highlight the successful public education and preparedness training from Japan's seismic culture, because the relatively poor understanding of an EEWS by the public can result in confusion. Yet, beyond what actions are necessary to take in response to warnings (Ji et al., 2019; Sutton et al., 2020), the public also needs education regarding the technical limitations and accuracy of EEWSs (Kamigaichi et al., 2009). We also suggest that Chinese scholars should focus more efforts on the public response to and perception of EEWSs to get more insights for issuing alerts, managing emergencies, and making policy.

In addition, due to differences in geological setting, socio-economic development status, and population density, losses caused by earthquakes of the same magnitude can vary greatly. Therefore, it is also very important to decide where an EEWS should be set up. Since earthquakes are disasters faced by many countries, collaboration in development and application of EEWSs among countries or regions should be encouraged, so that appropriate efforts are made to reduce loss of life and property when earthquakes occur, despite their inability to reduce losses in epicenter areas.

5 Conclusion

The Changning Earthquake warning event demonstrated that EEWSs are not simply technological engineering infrastructure, but they are also social systems for disaster mitigation. There will be no substantive benefit without proper knowledge and appropriate emergency responses by the public, even if the warning is issued accurately and timely, as evidenced by the facts of Mexico and Chengdu, China. Although authoritative government agencies have emphasized that information release

[2] Sichuan Seismological Bureau organized institutions to complete the drafting of "emergency earthquake information release earthquake warning information". The local standard draft was published for public comments. http://www.scdzj.gov.cn/jlhd/yjzj/202004/t20200429_54006.html (Accessed on 29th April, 2020)

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services are the "last kilometer" for earthquake warning systems to reach the public, the actual implementation showed that the "last kilometer" was not obstacle-free. It is worth consideration about how to timely release and effectively convey early warning information based on China's actual reality, not an idealized situation. The construction of EEWSs, issuance of alarms to the public, and formation of public awareness by science education are inseparably related. We recommend that China should collect best practices of EEWS utilization domestically and internationally in cases of EEW alert delivery to the public for the purpose of more effective promotion of EEW and collaboration among countries would benefit many people in the world.

Author contributions

YT and XQ designed the research. MZ and XQ performed the data curation, formal analysis, and wrote the original paper. YT, XQ and BCS were responsible for supervision. All authors participated in improving the paper by editing.

Competing interests

The authors declare that they have no conflict of interest.

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