Paper:

JMA's Tsunami Warning for the 2011 Great Tohoku Earthquake and Tsunami Warning Improvement Plan

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The Japan Meteorological Agency (JMA) issued a timely tsunami warning three minutes after the 2011 off the Pacific coast of Tohoku Earthquake (the Great Tohoku Earthquake) occurred at 14:49 (JST) on March 11, 2011. However, predicted tsunami heights at the early stage were greatly underestimated. Based on lessons learned from this earthquake, the JMA plans to improve its tsunami warning.

Keywords: The 2011 off the Pacific coast of Tohoku Earthquake, tsunami warning improvement

1. Introduction

The Japan Meteorological Agency (JMA) issued a tsunami warning on March 11, 2011, for the 2011 off the Pacific coast of Tohoku Earthquake (the Great Tohoku Earthquake) at 14:49 based on a promptly estimated magnitude of 7.9. It was about three minutes after the earthquake occurred, and a warning of "Major Tsunami," which is the largest category of tsunami warning in Japan, was issued for Iwate, Miyagi and Fukushima prefectures. Predicted tsunami heights were 3 m, 6 m and 3 m respectively. The JMA later upgraded the tsunami warning based on offshore and coastal tidal observation data. However, maximum tsunami heights observed along the coast from Iwate to Fukushima were eventually over 10 meters (Japan Meteorological Agency, 2011a [1]; The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011 [2]). This event revealed several problems about the JMA's tsunami warning, especially in the initial stage of the event. After the Great Tohoku Earthquake, and with the help of experts and related organizations, the JMA started to investigate what were the problems of JMA's warning for the event, and considered measures for improving tsunami warning/information. Taking into account advisors' suggestions, the JMA summarized a tsunami warning improvement plan in March 2012 (Japan Meteorological Agency, 2012a [3]). In this paper, I briefly introduce the JMA's tsunami warning system and explain its tsunami warning for the Great Tohoku Earthquake, together with an outline of the tsunami warning improvement plan based on lessons learned from the event, based on previous reports of Ozaki (2011) [4] and Hoshiba and Ozaki (2012a, b) [5, 6].

Table 1. Current tsunami warning/advisory categories.

Category		Predicted tsunami height	
Tsunami Warning	Major tsunami	3 m, 4 m, 6 m, 8 m and 10 m or more	
_	Tsunami	1 m, 2 m	
Tsunami Advisory		0.5 m	

2. JMA Tsunami Warning System

The JMA started current tsunami warning operations based on a quantitative tsunami prediction system in 1999. This system stores more than 100,000 scenarios of precalculated tsunami propagation simulation as a database. Each scenario links specific assumed hypocenter locations – intervals of a half degree near the coast of Japan and one degree far off Japan at 120E-157E and 20N-52N; focal depth - 0 km, 20 km, 40 km, 60 km, 80 km and 100 km; and magnitude -8.0, 7.4, 6.8 and 6.2 - to resultscalculated for coastal tsunami height distribution. When an earthquake occurs, the hypocenter, focal depth and magnitude are quickly determined and several close scenarios are retrieved from the database. A tsunami warning is composed from retrieved discrete scenarios by means of interpolation/extrapolation or by enveloping the most probable scenarios. It takes about three minutes from the occurrence of an earthquake to the issuing of a tsunami warning. The JMA's qualitative tsunami prediction system has been showing performance rather overestimated than underestimated, reflecting the concept of the system that warnings should be based on worst-case scenarios. After issuing a tsunami warning, the JMA monitors online sea level data, and if it shows the possibility of a tsunami larger than predicted, the issued warning will be promptly updated. (Details of the JMA tsunami prediction system are described in Tatehata (1998) [7] and Kamigaichi

The JMA has two categories for tsunami warnings and one for advisories determined by predicted tsunami height (**Table 1**). Tsunami warnings/advisories are provided to 66 areas into which the coastal line of Japan is divided. Predicted tsunami height and arrival time are also announced in addition to these categories. The JMA mon-

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Table 2. Abstract of chronology of JMA tsunami warnings/advisories and observations.

Time (JST)	Warning/Advisory	Observations	Magnitude
14:46, March 11, 2011 (Earthquake)		From just after the quake, several Tohoku stations showed receding sea levels.	
14:49	1 st warning/advisory (Iwate: 3 m, Miyagi: 6 m, Fukushima: 3 m, etc.),		Mjma7.9
14:55			PTWC 1 st bulletin (M7.9)
14:58		Sharp rise in sea level (Off Kamaishi's pressure sensor)	
15:12		6.6 m (Off Kamaishi GPS buoy)	
15:13		6.2 m (Off Miyako GPS buoy)	
15:14	2 nd warning/advisory (Iwate: 6 m, Miyagi: 10 m or more, Fukushima: 6 m, etc.) <1 st upgrade>		
15:15		5.6 m (Off Kesennuma GPS buoy)	
15:18		8.0 m (Ofunato)	
15:21		4.2 m (Kamaishi)	
15:26		8.5 m (Miyako) 8.6m (Ayukawa)	
15:30	3rd warning/advisory (Iwate, Miyagi and Fukushima:10 m or more, etc.) <2nd upgrade>		
15:40			Mw8.8 was obtained
15:43			PTWC 2 nd bulletin (Mw8.8)
15:51		9.3 m (Soma)	
16:00			Mjma8.4 (Press release)
16:08	4 th warning/advisory <3rd upgrade>		
17:30			Mw8.8 (Press release)
18:47	5 th warning/advisory <4 th upgrade>		
21:35	6 th warning/advisory <5 th upgrade>		
22:53	7 th warning/advisory <6 th upgrade>		
03:20, March 12	8 th warning/advisory <7 th upgrade>		
13:50	9 th warning/advisory <1 st downgrade>		
20:20	10 th warning/advisory <2 nd downgrade>		
07:30, March 13	Advisory <3 rd downgrade>		
17:58	Advisory <4 th downgrade>		

Note: All coastal observation data listed above were disrupted because of wash out etc., and tsunami heights at coast might be higher.

itors tsunami for observations in real time with 173 tide gauges and 15 GPS buoys as of January 2012. When a tsunami is actually observed, information on observation is disseminated. Tide gauges are operated by the JMA, the Cabinet Office, the Ports and Harbors Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the Japan Coast Guard, the Geospatial Information Authority of Japan (GSI) and local governments. GPS buoys are located 10 to 20 km off the coast, and operated by the Ports and Harbors Bureau. These data are used for not only tsunami observation information but also for tsunami warning updates, if necessary.

3. JMA Tsunami Warning for the Great Tohoku Earthquake

The chronology of JMA's tsunami warning/advisories and observations is summarized in **Table 2**. The JMA issued the initial tsunami warning for the Great Tohoku Earthquake at 14:49 on March 11, together with "Major Tsunami" warnings for Iwate Prefecture at a predicted height of 3 m, for Miyagi Prefecture at a predicted 6 m and for Fukushima Prefecture at a predicted 3 m. It was issued based on the promptly estimated magnitude of 7.9 in JMA magnitude (Mjma) (Katsumata, 2004 [9]). It was regarded as reasonable because the value and hypocenter location were close to that of the earthquake officially

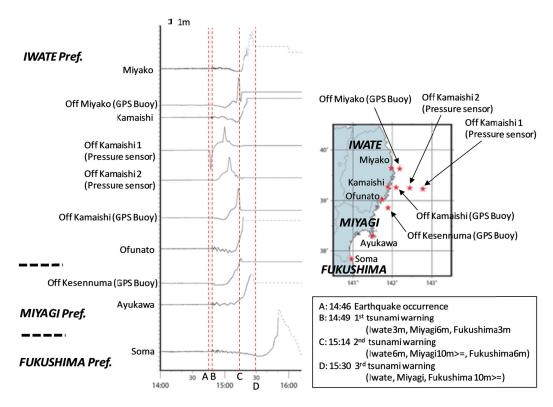


Fig. 1. Coastal and offshore sea level observations data for the period of the three initial tsunami warnings. Dotted lines in observation curves indicate data recovered afterward through site surveys.

anticipated off the coast of Miyagi prefecture. After the first warning, the JMA updated tsunami warnings seven times – at 15:14, 15:30, 16:08, 18:47, 21:35, and 22:53 on March 11, and at 03:20 on March 12 – based on offshore and coastal tsunami observations. According to the site survey of the 2011 Tohoku Earthquake Tsunami Joint Survey Group (2011) [2], the tsunami reached more than 10 meters high along the coast from Iwate to Fukushima Prefecture. Although the JMA upgraded tsunami height predictions to 10 m or more for Miyagi at 15:14 and Iwate and Fukushima at 15:30, initial tsunami warnings underestimated tsunami height. There was also the possibility that such a low tsunami height prediction could have been one cause for residents to refrain from evacuating.

Mjma, which is used for the first issuance of a tsunami warning, is based on the maximum displacement amplitude of strongmotion seismometers and has the advantage of quick availability. However, due to dependence on the short period (-10 sec.) wave component, Mjma is prone to underestimating gigantic or tsunami earthquakes. The JMA, therefore, also calculates moment magnitude (Mw) within 15 minutes of an earthquake using domestic broadband seismic waveform data to obtain an appropriate estimate of magnitude even for gigantic or tsunami earthquakes, and the initial warning is updated using Mw, if necessary.

At the time of the Great Tohoku Earthquake, the JMA also tried to calculate Mw by using domestic broadband seismic waveform data. However, this could not be obtained because of scale out records at most of

the broadband stations in Japan, and Mw8.8 was finally calculated by collecting unsaturated overseas broadband records about 55 minutes after the earthquake occurrence, i.e., around 15:40. 57 minutes after the quake, i.e., 15:43, the JMA received a second bulletin of a tsunami warning from the Pacific Tsunami Warning Center (PTWC), which included an updated magnitude of 8.8. These values were not utilized for warning updates because the tsunami height prediction based on Mw8.8 was similar to the already updated warning at 15:30 described below.

After the first warning was issued, the JMA intensified tsunami monitoring and found a large sea level rise in a cable-type pressure sensor deployed by the Earthquake Research Institute (ERI) of the University of Tokyo at 14:58. Subsequently, an abrupt sea level rise was noted in data from GPS buoys deployed off of Iwate and Miyagi prefectures at 15:10, and the JMA upgraded the tsunami height prediction from 6 m to over 10 m for Miyagi Prefecture and from 3 m to 6 m for Iwate and Fukushima prefectures at 15:14. It took 28 minutes from earthquake occurrence, and a large tsunami had already reached part of the Iwate coast by this time. After confirmation of the data from GPS buoys and tide gauges, the JMA updated tsunami warning again at 15:30, including an upgrade of tsunami height prediction from 6 m to over 10 m for Iwate and Fukushima prefectures. These upgrades were based on GPS buoy data multiplying an empirically determined amplification coefficient to estimate coastal tsunami height. Cable-type pressure sensors, which are located more offshore than GPS buoys, were not used for the upgrade because the method for utilizing them in tsunami warnings was still under development. The above mentioned observation data and tsunami warning issuance timing are summarized in **Fig. 1**.

The first tsunami observation information issued at 14:59 stated that "the initial wave height is 0.2 m." This message might have led to delays or interruptions in the evacuation of residents who had misunderstood that the arriving tsunami was a small one.

4. Lessons Learned from the Great Tohoku Earthquake and Tsunami Warning Improvement Plan

The Great Tohoku Earthquake generated huge damage and had left more than 19,000 people dead or missing as of March 2012 (Fire and Disaster Management Agency, 2012) [10]. Considering the devastation caused by the Great Tohoku Earthquake seriously, the JMA held advisory meetings on the improvement of the JMA's tsunami warning inviting tsunami experts, local governments, broadcasting companies and other relevant organizations to take part. In cooperation with the Cabinet Office and the Fire and Disaster Management, the JMA also conducted surveys on the utilization of tsunami warning and residents' evacuation activities at the time of the Great Tohoku Earthquake. Based on discussions at advisory meetings, surveys and public comments, a "Direction for JMA Tsunami Warning Improvement" was prepared in September 2011 [11], and a "Recommendation on Tsunami Warning Criteria and Expression of Warning Messages" was prepared in February 2012 [12]. These documents were combined into a "JMA Tsunami Warning Improvement Plan" in March 2012 [3]. The lessons learned from the Great Tohoku Earthquake and the plan on tsunami warning improvement summarized in the JMA Tsunami Warning Improvement Plan are described below.

4.1. Basic Policy on Tsunami Warning Improvement

4.1.1. Early Warning and Update

Considering the fact that about 40% of tsunamigenic earthquakes around Japan have caused tsunami that struck the Japanese coast within 20 minutes of earthquake occurrence and that there were damaging tsunamis that hit the coast within several minutes, first warnings have to be disseminated as soon as possible, preferably within three minutes. After that, tsunami warnings should be updated using as much available seismic and sea-level data as possible. The possibility that updated warnings may not reach residents due to power outage or communication link failures should also be considered.

4.1.2. Safe-Side Warnings

In the very early stage after the occurrence of an earthquake, there remains large uncertainty in tsunami source

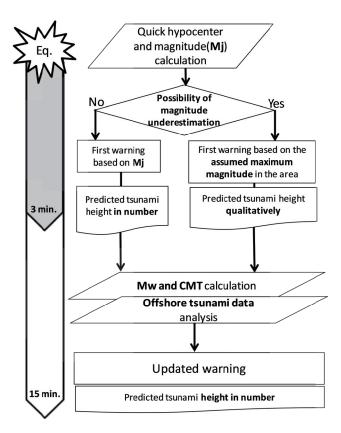


Fig. 2. Flowchart of planned improved tsunami warning procedure.

estimation. The first warning issued under such circumstances should be made based on the worst possible case within the uncertainty involved.

4.2. Technical Issues

Considering the importance of the first warning together with the safe-side warning policy, we need to take measures to avoid underestimation in the first warning even if the event is gigantic. As there is no method for estimating magnitude much larger than 8 precisely in three minutes, we will introduce a tool that warns of the possibility of Mjma underestimation in three minutes. In case that an underestimation possibility is detected, we will issue tsunami warnings based on the assumed maximum magnitude around the area. The tool is now under development, and possible candidates include measuring the extent of a strong ground motion area and monitoring long-period seismic waves.

Warnings based on the worst case should be updated at appropriate levels by applying Mw that expresses the precise scale of an earthquake. Considering the fact that most of the domestic broadband seismometers could not record the large seismic wave amplitudes of the Great Tohoku Earthquake and that Mw was not calculated, we will install a network of broadband strongmotion seismometers that give us full records of broadband seismograms. Further, as there are cases in which the earthquake scale does not give an appropriate tsunami source estimation,

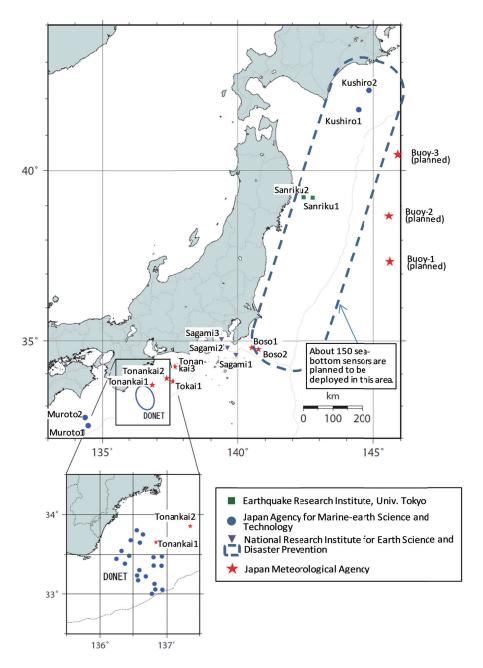


Fig. 3. Current and planned sea-bottom pressure sensors around Japan.

e.g., tsunamis caused by submarine landslides, methods to update tsunami warnings based on offshore tsunami observation are important. The JMA is also developing a method to estimate tsunami height at coasts using offshore tsunami observation results – which includes not only GPS buoy data but also sea-bottom pressure sensor data – by inferring initial tsunami height distribution applying an inversion technique. According to research on this method applied in past events, it shows reliable performance in tsunami height estimation at coasts including the case of the Great Tohoku Earthquake (Tsushima et al., 2009, 2011, 2012 [13-15]). In addition to such technical skill development, sea-bottom pressure sensors are going to be deployed more densely in cooperation with related organizations. As an urgent measure, the JMA it-

self has a plan to deploy three DART buoys far off the Pacific coast of Tohoku this year. It is an urgent measure and the buoy type was adopted considering that it can be deployed in a shorter time than cable-type pressure sensors. The planned locations are in a very low seismicity area about 150 km east of the Japan Trench with the aim of separating tsunami signals from noisy earthquake-induced pressure vibration.

A flowchart of planned improved tsunami warning procedure is shown in **Fig. 2**, and current and planned seabottom pressure sensors are shown in **Fig. 3**.

4.3. Warning Criteria and Message

At the time of the Great Tohoku Earthquake, the underestimated tsunami height predictions of "3 m" and "6 m"

Category		Present (as of Feb. 2012)	Improvement Plan		
		Expression of Tsunami height	Expression of Tsunami height		Predicted height
			Numerical	Qualitative	Fredicted height
Tsunami Warning	Major Tsunami	10 m or more, 8 m, 6 m, 4 m, 3 m	Over 10 m	Huge	10 m-
			10 m		5 m to 10 m
			5 m		3 m to 5 m
	Tsunami	2 m, 1 m	3 m	High	1 m to 3 m
Tsunami Advisory		0.5 m	1 m	(Blank)	0.2 m to 1 m

Table 3. Categories and criteria of tsunami warning and tsunami height prediction.

were reportedly considered one cause for residents to refrain from evacuating. It is reported that there were people who thought a high neighboring dike would block a tsunami of such a height. In order to avoid such problem, predicted tsunami heights will not stated in numbers in the initial warning which is based on assumed maximum earthquake magnitude around the area. This is because large uncertainty in tsunami source estimation remains at this stage and derived tsunami height prediction thus does not have enough accuracy for people to rely on. Therefore, instead of numbers, tsunami height prediction is expressed qualitatively, e.g., as "Huge" or "High" aiming at telling people the risk of the impending huge tsunami arrival.

Warning criteria were reexamined through an investigation of the relationship between damage and tsunami height at coast close to the damaged area and of site survey results on the relationship between inundation depth and damage (Japan Meteorological Agency, 2012b [12]). Almost all data were from the Great Tohoku Earthquake cases. The lower bound for the "Tsunami" grade for which damage to land area is expected and evacuation instructions by local authorities are necessary, was confirmed to be 1 m, corresponding to the lower limit of inundation. That for the "Major Tsunami" grade, for which tremendous damage is expected to land areas, was confirmed to be 3 m, at which the rate of severe damage to wooden houses increases.

Tsunami height categorization will be lowered from eight -0.5m, 1m, 2m, 3m, 4m, 6m, 8m, and ≥ 10 m - to five -1m, 3m, 5m, 10m, and >10m -, taking into account the limited variation in executable countermeasures in case of emergency and forecast error range. The estimated tsunami height indicated in the warning message is the upper bound of predicted heights for the area. **Table 3** summarizes numerical and qualitative expressions of tsunami height prediction and criteria of tsunami warning/advisory described in the improvement plan.

As for the tsunami observation information, arrival time and initial polarity are mentioned from the very beginning, because conveying the fact that "a tsunami has arrived" is important to urge residents to evacuate. Observed tsunami height is mentioned only after it grows larger than criteria one grade below the presently valid warning or advisory, e.g., 1 m when a "Major Tsunami"

is valid, so as not to underestimate the threat to residents. The JMA plans to start the above described improvement measures by March 2013.

5. Summary

Considering the lessons learned from the Great Tohoku Earthquake, the JMA plans to improve its tsunami warning, and transition to new operations is scheduled to be in March 2013. Even before the final transition, useful techniques that become available will be included in current operations. Specifically, preliminary versions of a tool for warning of the underestimation of Mjma have already been introduced on a trial basis and are in the process of being evaluated and revised. The JMA will continue to review its tsunami warning from the viewpoint that it works as information that protects people's lives.

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