Outline of the 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0) —Tsunami warnings/advisories and observations—

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The Japan Meteorological Agency (JMA) is the sole authority to issue domestic tsunami warnings/advisories to the public in Japan. JMA issues the tsunami warnings/advisories based on hypocentral parameters such as location, depth and magnitude, and the tsunami-simulation database system which stores more than one hundred thousand cases of previously-conducted tsunami-propagation simulation results. This system enables tsunami warnings/advisories to be issued within about three minutes after events. For the devastating tsunami generated by the 2011 off the Pacific coast of Tohoku Earthquake on March 11, 2011, this system successfully functioned and the first warning was issued at 14:49 (Japan Standard Time), which was about three minutes after the occurrence of the earthquake. JMA also monitors sea-level data observed with 172 tide gauges and 12 GPS buoys (there were 11 at the time of the earthquake, and this increased to 12 in May 2011), and they are used for changing grades and areas of tsunami warnings/advisories. This time JMA raised tsunami-warning grades and widened warning areas seven times, and downgraded or cancelled the warnings/advisories four times. Mainly based on tsunami observations, all tsunami warnings/advisories were cancelled at 17:58 on March 13. This was about 2 days and 3 hours after the tsunami warning was issued.

Key words: The 2011 off the Pacific coast of Tohoku Earthquake, tsunami warning, tsunami observations.

1. Introduction

The 2011 off the Pacific coast of Tohoku Earthquake generated a devastating tsunami. This event recorded the largest observed tsunami height (9.3 m) on a tide gauge since the Japan Meteorological Agency (JMA) started national tsunami-warning operations in 1952. In 1999, JMA introduced a quantitative tsunami-warning system to its existing tsunami-warning categories, consisting of "Major Tsunami" warning, "Tsunami" warning and Tsunami advisory (Table 1), and 66 individual regions for providing a Tsunami warning/advisory. For the first time since the introduction of the current system, JMA issued a tsunami-height estimation of 10 m or more, and issued "Major Tsunami" warnings for the widest areas. This was also the first time JMA issued tsunami warnings and/or advisories for Japan's entire coastline.

2. Tsunami Warnings/Advisories and Observations

JMA issued tsunami warnings/advisories for the destructive tsunami for coasts ranging from Hokkaido to Kyushu, and the Ogasawara islands, within about three minutes after the earthquake. The initial warning issued at 14:49 on March 11 was based on the promptly-estimated JMA Magnitude of 7.9, and "Major Tsunami" warnings were issued to the areas of Iwate prefecture, Miyagi prefecture and Fukushima prefecture. At the same time, "Tsunami" warnings and Tsunami advisories were issued for many other areas (Fig. 1). After that, JMA raised tsunami-warning grades and widened warning areas in accordance with tsunami-height observations, and eventually, JMA issued tsunami warnings or advisories for Japan's entire coastline at 3:20 on March 12 (Fig. 2).

JMA monitors sea-level changes at 172 tide gauge stations, and 12 GPS buoys located about 10 to 20 km off the coast and maintained by the Ports and Harbours Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Observed tsunami heights are used for both supplementary tsunami information and changing grades or areas of tsunami warnings/advisories. During the event, JMA raised tsunami-warning grades and widened warning areas seven times (at 15:14, 15:30, 16:08, 18:47, 21:35, 22:53 on March 11, and 3:20 on March 12), and these upgrades were mainly based on tsunami observations. The tsunami-warning upgrades at 15:14 and 15:30 were based on the tsunami-wave observation at the GPS buoys, and the estimated tsunami heights at the coast deduced from the offshore data. As Fig. 4 shows, GPS buoys' data showed a steep rise about 5–10 minutes before the arrival of the significant tsunami waves on the coast. Other upgrades were conducted for regions where the ongoing estimations were considered to be underestimated in view of the trend of the sea-level variation up to that time.

The promptly-estimated M 7.9 was based on M_{jma}, which is the combination of the displacement magnitude for relatively-large earthquakes and the velocity magnitude for relatively-small earthquakes (Katsumata, 2004; Funasaki

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Table 1. JMA's tsunami warning/advisory categories.

Category		Explanation	Forecast tsunami height
Tsunami warning	Major tsunami	Tsunami height is expected to be 3 meters or more.	Forecast heights are specified for every region using values of 3 m, 4 m, 6 m, 8 m and 10 m or more.
	Tsunami	Tsunami height is expected to be up to 2 meters.	Same as above, using values of 1 m or 2 m.
Tsunami advisory		Tsunami height is expected to be about 0.5 meters.	0.5 m

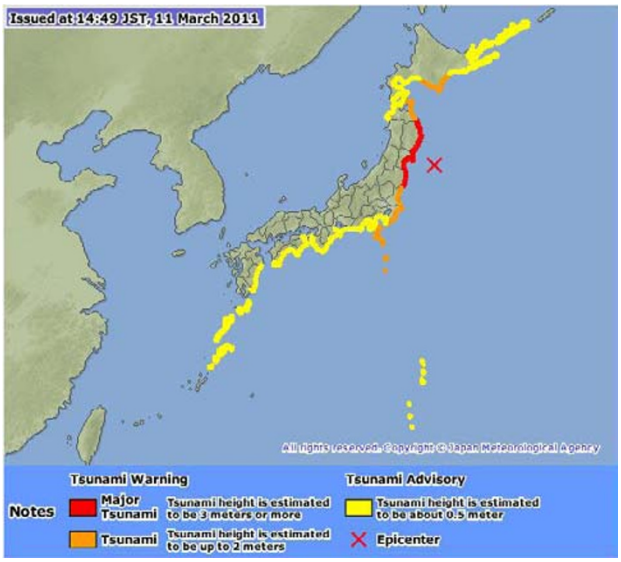

Fig. 1. Tsunami warnings/advisories issued at 14:49 of March 11.

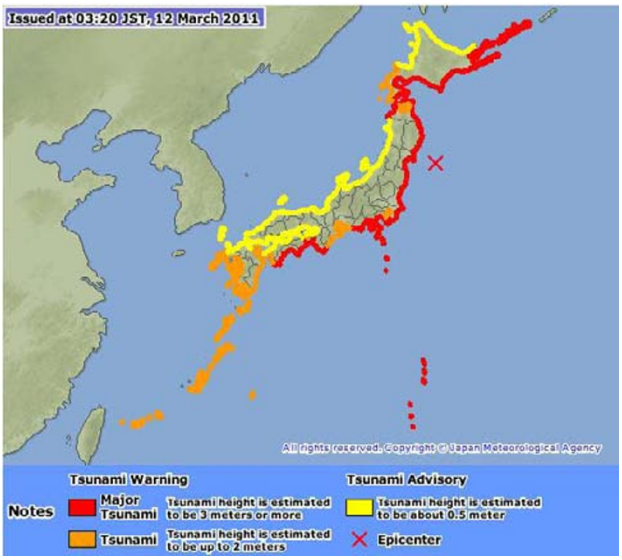

Fig. 2. Tsunami warnings/advisories issued at 3:20 of March 12.

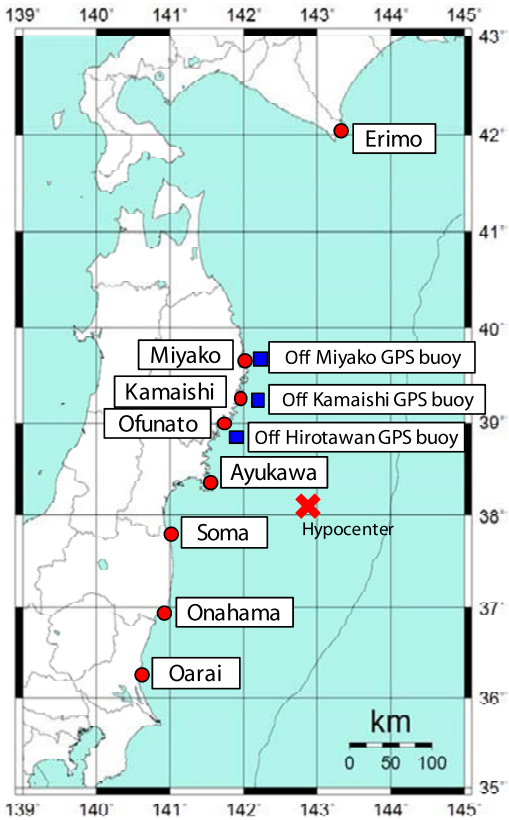

Fig. 3. Locations of tide gauges and GPS buoys shown in Table 2 and Figs. 4, 5 and 6.

and Earthquake Prediction Information Division, 2004). It can be calculated within several minutes, but it has a downside to be saturated for a magnitude substantially larger than 8. JMA updated M_{jma} to 8.4 at 16:00 and determined the moment magnitude (M_{w}) as 8.8 by CMT analysis at 17:30, which was calculated from overseas broadband seismic data. On March 13, M_{w} was revised to be 9.0 by CMT analysis using a longer range of filter (Hirose *et al.*, 2011). These revised values were not used for the updates of tsunami warnings, because updates based on sea-level observations had provided a substantially large tsunami-height estimation before these larger-magnitude values were obtained. To obtain M_{w} earlier should be one of the most important tasks for JMA to solve.

Just after the occurrence of the event, several tide gauges close to the hypocenter observed the initial sea-level changes (Fig. 5). According to the estimation by the Geospatial Information Authority of Japan (GSI) with its nationwide GPS network, the Pacific coastal region of Tohoku close to the epicenter sank up to about 1 meter as the result of the earthquake fault displacement (GSI, 2011). This displacement was considered to continue for about

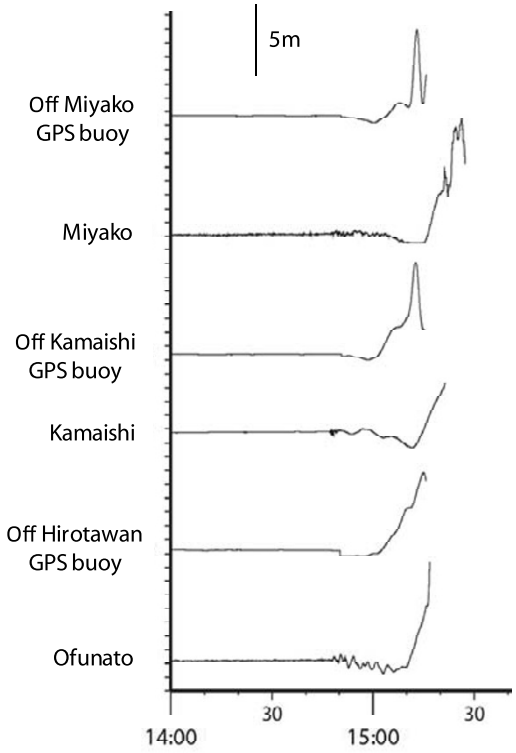

Fig. 4. Tsunami records at GPS buoys and tide gauges close to the buoys.

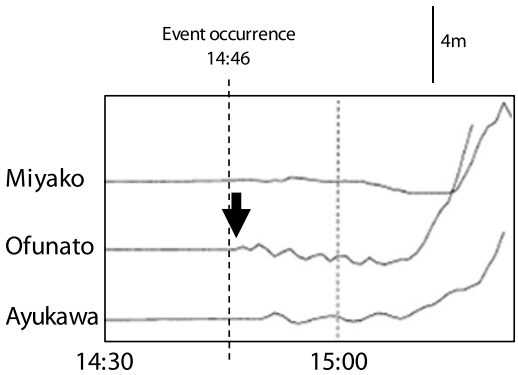

Fig. 5. Tsunami records at tide gauges close to the hypocenter. Time series are modified from JMA's 1st press release on the 2011 off the Pacific coast of Tohoku Earthquake (JMA, 2011a). Locations of tide gauges are shown in Fig. 3.

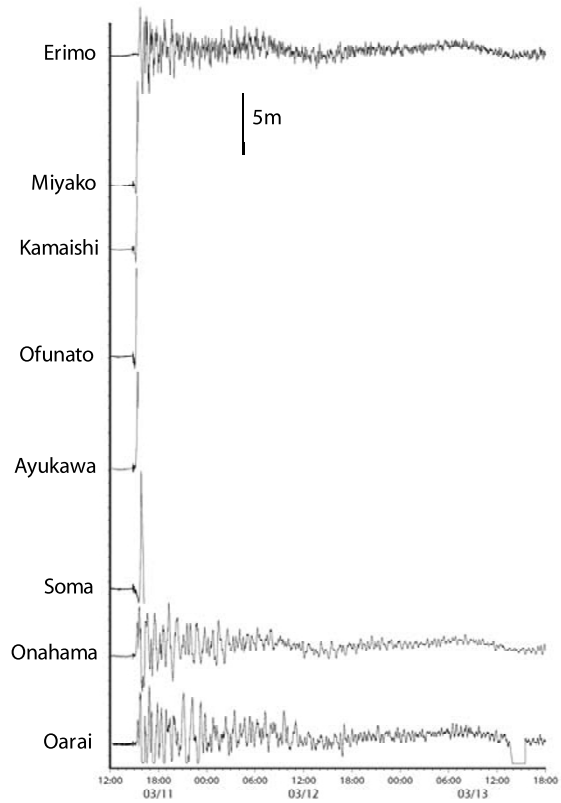

Fig. 6. Tsunami records at tide gauges shown in Table 2.

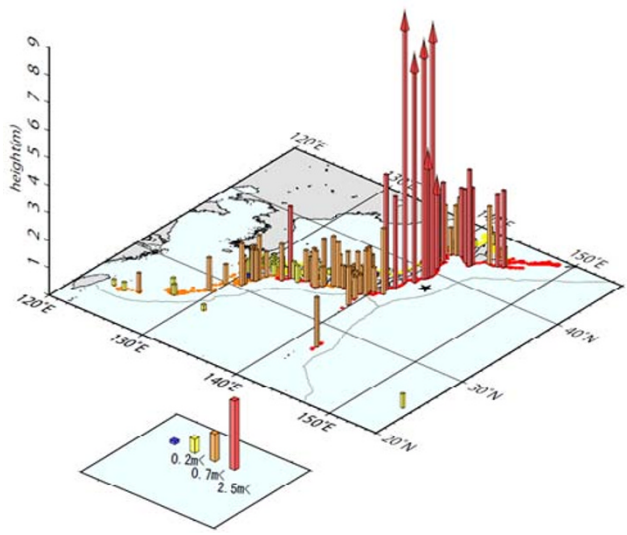

Fig. 7. Observed tsunami heights at tide gauges. Measurements are preliminary and will be reviewed and finalized following further investigations. Legend scale shown in lower middle.

three minutes (JMA, 2011b) and simultaneously caused the subsidence of the Pacific coast of Tohoku, which resulted in a large tsunami wave source region which extended to the Pacific coastline of Tohoku. According to the study by the Meteorological Research Institute (MRI), this was about 550 kilometers in length and 200 kilometers wide, ranging from off Iwate prefecture to off Ibaraki prefecture and reaching the Pacific coastline of Tohoku (MRI, 2011). This region was estimated from the distances between sea-level stations and the tsunami-wave source region calculated from initial tsunami-wave arrival times at sea-level stations and estimated tsunami travel times.

Sea-level observation data presented in Fig. 5 includes broad information of sea-level changes inside the tsunami-wave source region. If the absolute sea level had not changed and only the coastal land and seabed had sank after the event, the tidal record would have shown a positive change. It may indicate that sea water also sank together with coastal land and seabed. Sea-level data in Fig. 5 shows small variations with a period of several minutes just after the event, but it cannot be specified whether they are rippling waves induced by strong ground-shaking or tsunami waves. On the other hand, the record of Ofunato shows a gradual sea-level decline with a longer period. This is

Table 2. Maximum tsunami heights for stations located from north (top) to south (bottom). Locations of stations shown in Fig. 3. Measurements are preliminary and will be reviewed and finalized following further investigations.

Tide gauge station	Maximum tsunami height	Observed or disrupted time
Erimo, Hokkaido pref.	3.5 m	15:44
Miyako, Iwate pref.	8.5 m or more (disrupted)	15:26
Kamaishi, Iwate pref.	4.2 m or more (disrupted)	15:21
Ofunato, Iwate pref.	8.0 m or more (disrupted)	15:18
Ayukawa, Miyagi pref.	8.6 m or more (disrupted)	15:26
Soma, Fukushima pref.	9.3 m or more (disrupted)	15:51
Onahama, Fukushima pref.	3.3 m	15:39
Oarai, Ibaraki pref.	4.0 m	16:52

considered to be a tsunami wave which was generated by the wide range of seabed deformation relatively close to the station. The causes of these various sea-level changes are to be further investigated.

On the Pacific coast of Tohoku, the first large tsunami wave heights were observed, or considered to have arrived, at around 15:30 (Figs. 6 and 7, and some preliminary measurements provided in Table 2). In this huge tsunami, many sea-level station data streams were disrupted by various causes, such as flooding or washout, electric power failure, and/or wiring disconnection. As a result, downgrade and cancellation of tsunami warnings were based mainly on data from sea-level stations that survived. For some stations, recording media and tsunami records were able to be retrieved after the event as part of JMA's post-tsunami field surveys (Ofunato of the Iwate prefecture, Miyako of the Iwate prefecture, and Ayukawa of the Miyagi prefecture). While these media preserved a slightly longer data record after online transmission ceased, even these time series were disrupted, implying that there must have been even larger tsunami heights at these stations (JMA, 2011c, d, e, f). Further tsunami records are available in the March 2011 issue of the Monthly Report on Earthquakes and Volcanoes in Japan (JMA, 2011g).

Tsunami warnings/advisories were cancelled or downgraded four times as tsunami waves attenuated in height and became less destructive. The first downgrade was issued at 13:50 on March 12, followed by the cancellation or downgrade of all "Major Tsunami" warnings at 20:20 on March 12, cancellation or downgrade of all "Tsunami" warnings at 7:30 on March 13, and cancellation of all Tsunami advisories at 17:58 on March 13.

3. Summary

For the 2011 off the Pacific coast of Tohoku Earthquake and tsunami, JMA issued tsunami warnings/advisories, as it usually does, in a timely manner. However, due to the disruption of sea-level data streams, it became impossible to continuously monitor tsunami waves and thus more difficult to decide when to change or cancel ongoing tsunami warnings/advisories. In addition, if M_w could be calculated earlier, the frequency of updates would be decreased and the first update might be issued earlier. To improve the warning system, JMA will be reviewing its tsunami warning/advisory issuing and cancelling methods, processes, and procedures.

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