The Eight Years of Earthquake Early Warning Operation in the Japan Meteorological Agency

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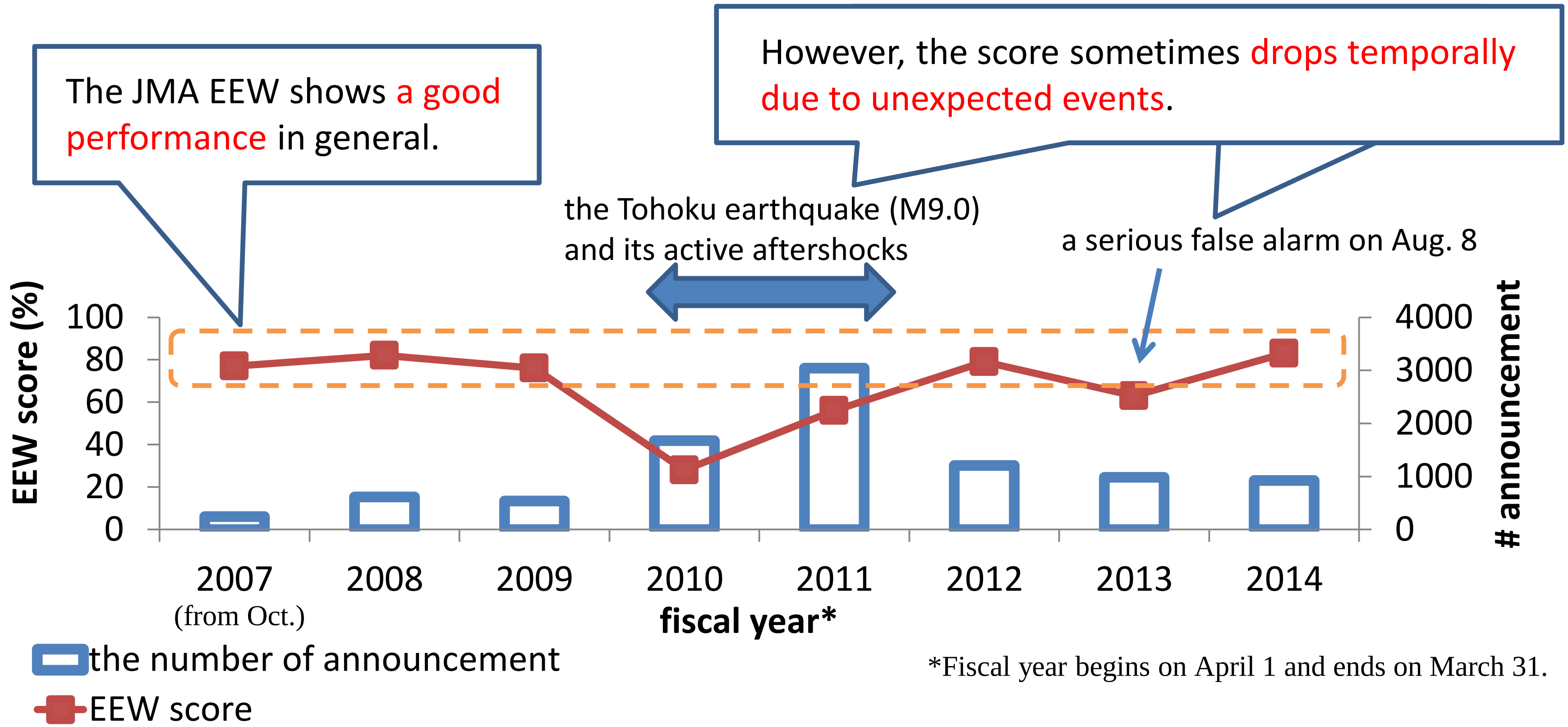
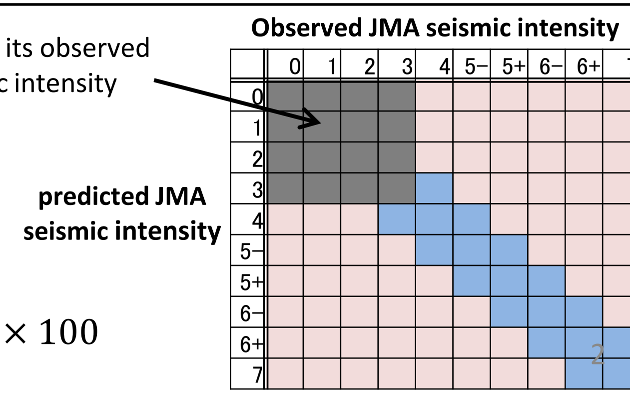
JMA EEW score from 2007 to 2014



*Fiscal year begins on April 1 and ends on March 31.

How to calculate the JMA EEW score

Definition:
a percentage of areas where an error of predicted JMA seismic intensity is within one degree



$$score = \frac{\#blue}{\#red + \#blue} \times 100$$

Contents

1. How does the JMA EEW work?

2. What technical challenges have occurred during the operation?

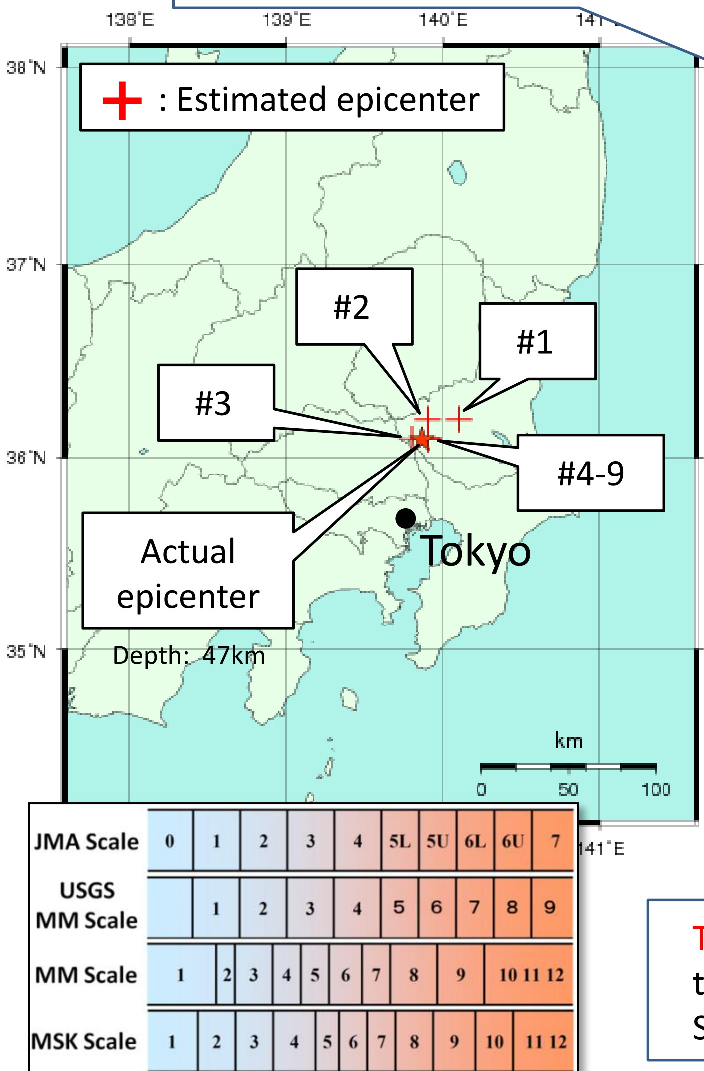
3. What improvements are planned?

1. How does the JMA EEW work?

ex.) a M5.6 earthquake on Sep. 16, 2014

EEW messages are calculated many times with additional observation data.

The JMA EEW estimates hypocenter location and magnitude and predicts JMA seismic intensity.



#	Issuance time	Lapse time	Lat.	Lon.	Dep.	Mag.	Maximum JMA seismic intensity
1	12:28:43.7	3.4	36.2	140.1	10km	4.1	3
2	12:28:43.9	3.6	36.2	139.9	10km	5.2	5lower
3	12:28:44.6	4.3	36.1	139.8	10km	5.3	5lower
4	12:28:44.8	4.5	36.1	139.9	60km	5.4	4
5	12:28:46.0	5.7	36.1	139.9	60km	5.7	4
6	12:28:51.2	10.9	36.1	139.9	50km	5.5	4
7	12:28:53.5	13.2	36.1	139.9	50km	5.5	4
8	12:29:10.2	29.9	36.1	139.9	40km	5.6	4
9	12:29:25.2	44.9	36.1	139.9	40km	5.6	4

Forecast

Warning

The general public receive an EEW message as "warning" when the maximum JMA seismic intensity reaches 5lower or more. Specific users obtain all EEW messages as "forecast".

(1) Hypocenter estimation

Earthquake occurrence → Lapse time

# triggered point	1	2	3	5 - 10

Main part

220 strong-motion seismometers (in 2014)

- B-delta method (joint research with RTRI)
- Territory method
- Grid search method — Using only P-wave arrivals

Sub part1

About **800 high sensitivity** seismometers (Hi-net)

- Grid search with Not-Yet-Arrived-Data (developed by NIED)

Sub part2

More than **1,000** seismometers

- Conventional auto hypocenter determination method — Using both P- and S-wave arrivals

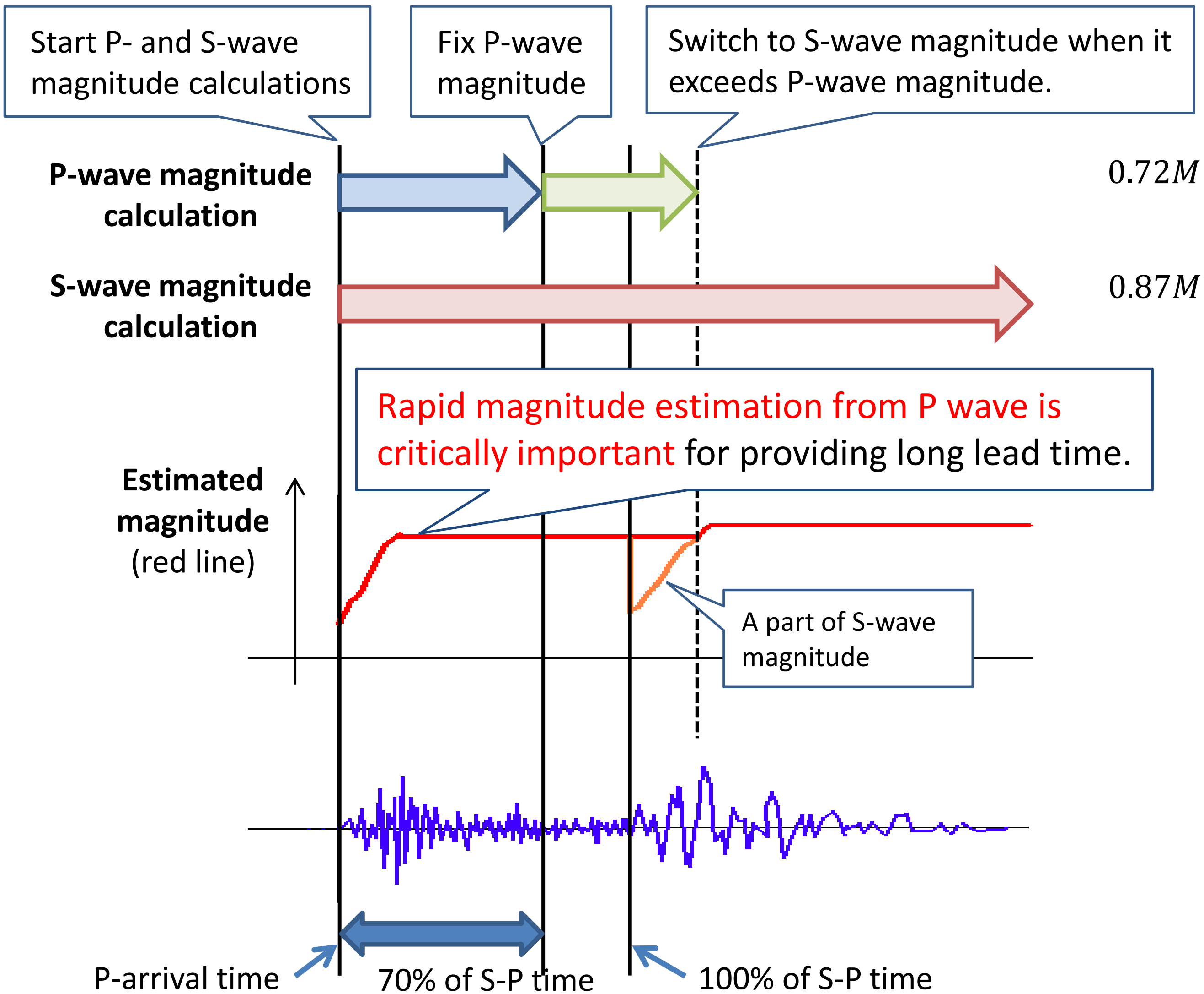
rapid ⟷ accurate

Main part network in 2014

RTRI : Railway Technical Research Institute
NIED : National Research Institute for Earth Science and Disaster Prevention

Detailed method

(2) Magnitude estimation



$$0.72M = \log A + 1.2 \log R + 5.0 \times 10^{-4} R - 5.0 \times 10^{-3} D + 0.46$$

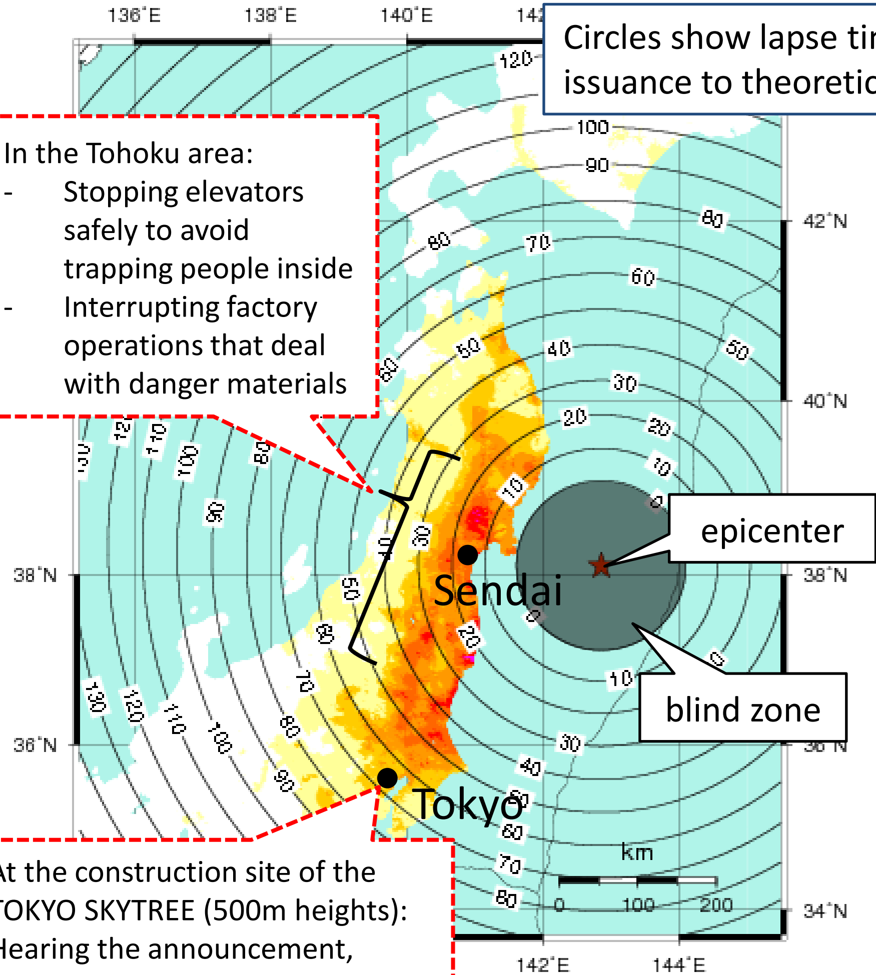
$$0.87M = \log A + 1.0 \log R + 1.9 \times 10^{-3} R - 5.0 \times 10^{-3} D + 0.98$$

A: maximum displacement amplitude /10μm
R: hypocentral distance /km
D: hypocenter depth /km

Real-life examples of disaster mitigation by the JMA EEW

The 2011 off the Pacific coast of Tohoku Earthquake (M9.0)

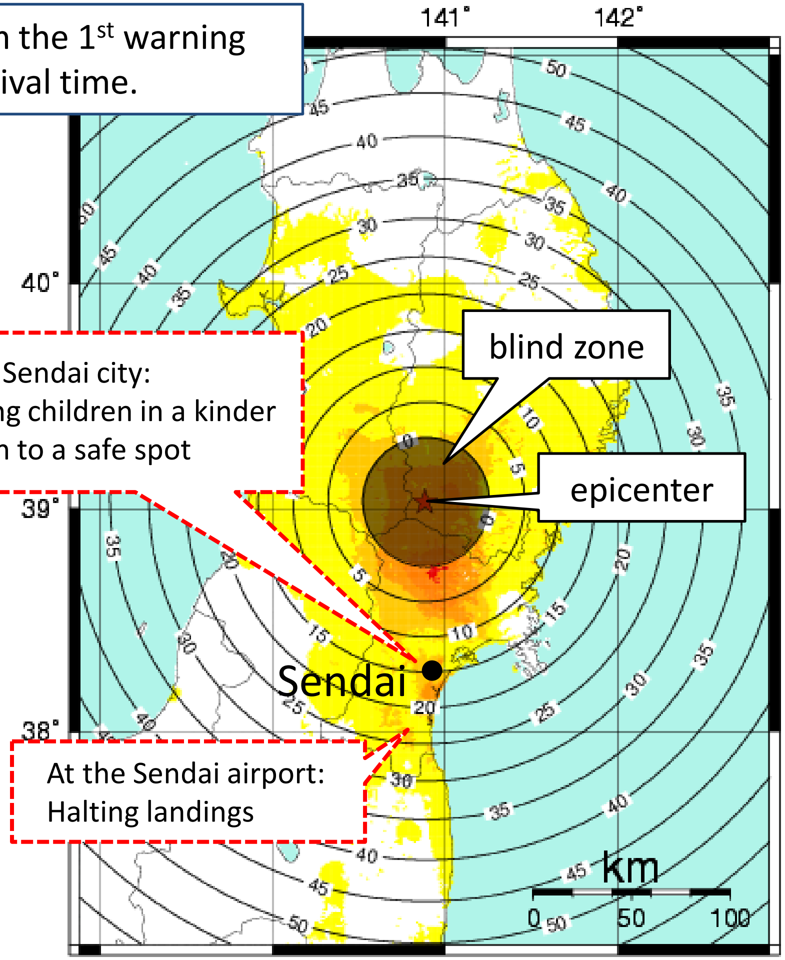
Circles show lapse time from the 1st warning issuance to theoretical S-arrival time.



In the Tohoku area:
- Stopping elevators safely to avoid trapping people inside
- Interrupting factory operations that deal with danger materials

At the construction site of the TOKYO SKYTREE (500m heights): Hearing the announcement, workers stopped operations and held on to pillars for their safety. (the Yomiuri Shimbun (newspaper) on June 2, 2014)

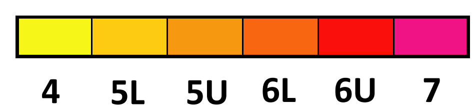
The Iwate-Miyagi Nairiku Earthquake in 2008 (M7.2)



In the Sendai city: Leading children in a kinder garden to a safe spot

At the Sendai airport: Halting landings

Observed JMA seismic intensity
(interpolated in 2-D)



2. What technical challenges have occurred during the operation?

(1) Under-prediction for huge earthquake

(2) False alarm with active aftershock and noise data

(1) Under-prediction for huge earthquake

Technical challenge

The JMA EEW under-predicted strong motion of the Tohoku earthquake because of
- **magnitude saturation**
- **large rupture zone point source model cannot represent adequately**

Measure

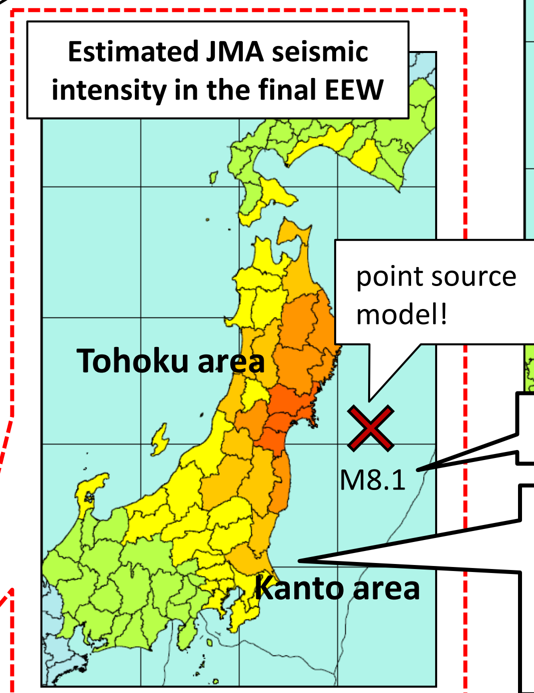
1. Upgrading the S-wave magnitude equation
- It estimates M8.5 and maximum JMA seismic intensity 7.
- A tentative countermeasure

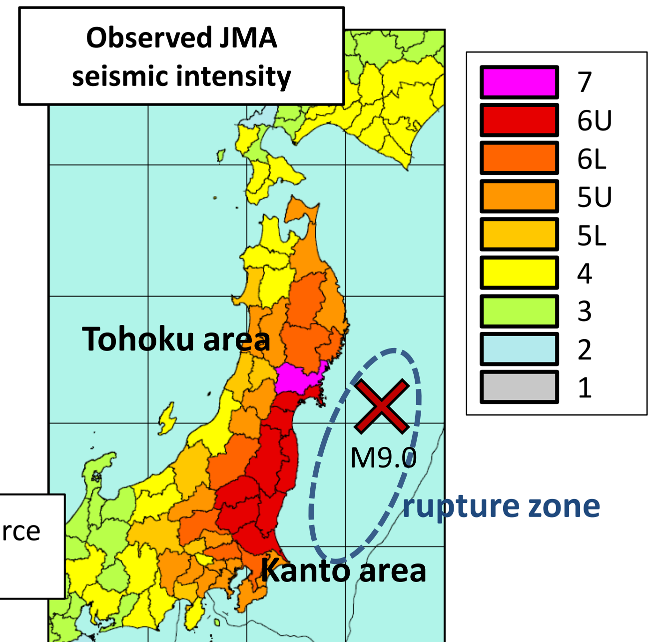
2. Introducing PLUM method (future planning)
- Prediction without hypocenter estimation
- An essential countermeasure

EEW announcements for the Tohoku earthquake

#	Lapse time	Lat.	Lon.	Dep.	Mag.	Maximum JMA seismic intensity
1	5.4	38.2	142.7	10km	4.3	**1**
2	6.5	38.2	142.7	10km	5.9	**3**
3	7.5	38.2	142.7	10km	6.8	**4**
4	8.6	38.2	142.7	10km	7.2	**5L**
5	9.6	38.2	142.7	10km	6.3	**4**
6	10.7	38.2	142.7	10km	6.6	**4**
7	11.0	38.2	142.7	10km	6.6	**4**
8	15.9	38.1	142.9	10km	7.2	**4**
9	22.2	38.1	142.9	10km	7.6	**5L**
10	30.0	38.1	142.9	10km	7.7	**5L**
11	45.0	38.1	142.9	10km	7.7	**5L**
12	65.1	38.1	142.9	10km	7.9	**5U**
13	85.0	38.1	142.9	10km	8.0	**5U**
14	105.0	38.1	142.9	10km	8.1	**6L**
15	116.8	38.1	142.9	10km	**8.1**	**6L**

An EEW warning was successfully issued for the Tohoku area. But…





Magnitude saturation happened.

The EEW couldn't predict high seismic intensities due to large extension of the rupture in the Kanto area.

(2) False alarm with active aftershock and noise data

Technical challenge

False alarms were issued because the JMA EEW system
- **confused small simultaneous multiple earthquakes with a single large earthquake large rupture zone.**
- **identified noise data as one of trigger data.**

Measure

1. Upgrading earthquake identification logic
- Setting more strict distance limitation and eliminating tiny earthquake data
- A tentative countermeasure

2. Introducing IPF method (future planning)
- Prediction using Bayesian estimation
- An essential countermeasure

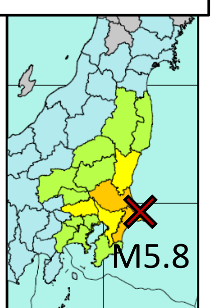
Simultaneous multiple earthquakes on May 28, 2011

EEW announcements

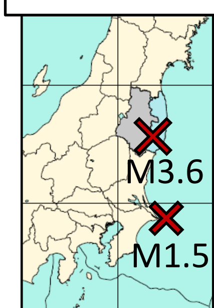
#	Lapse time	Lat.	Lon.	Dep.	Mag.	Maximum JMA seismic intensity
1	27.6	35.8	140.8	10km	5.8	**5L**
2	28.9	35.2	141.4	10km	6.1	**4**
3	29.3	37.0	140.7	10km	4.0	**3**
4	30.5	37.0	140.7	10km	4.0	**3**
5	50.4	37.0	140.7	10km	4.0	**3**
6	68.4	37.0	140.7	10km	4.0	**3**

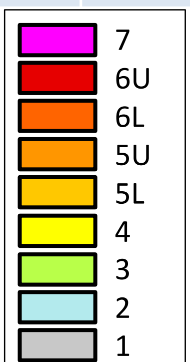
False warning!

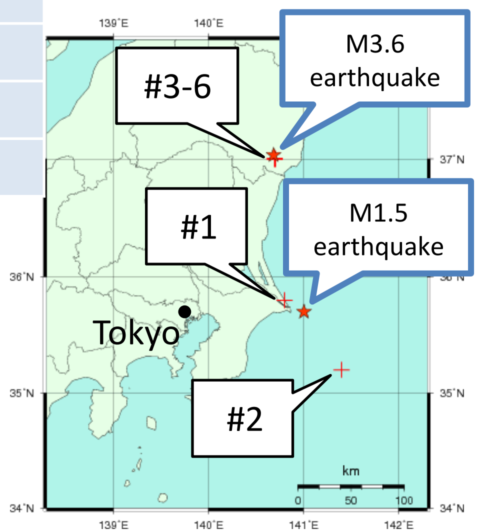
The 1st EEW



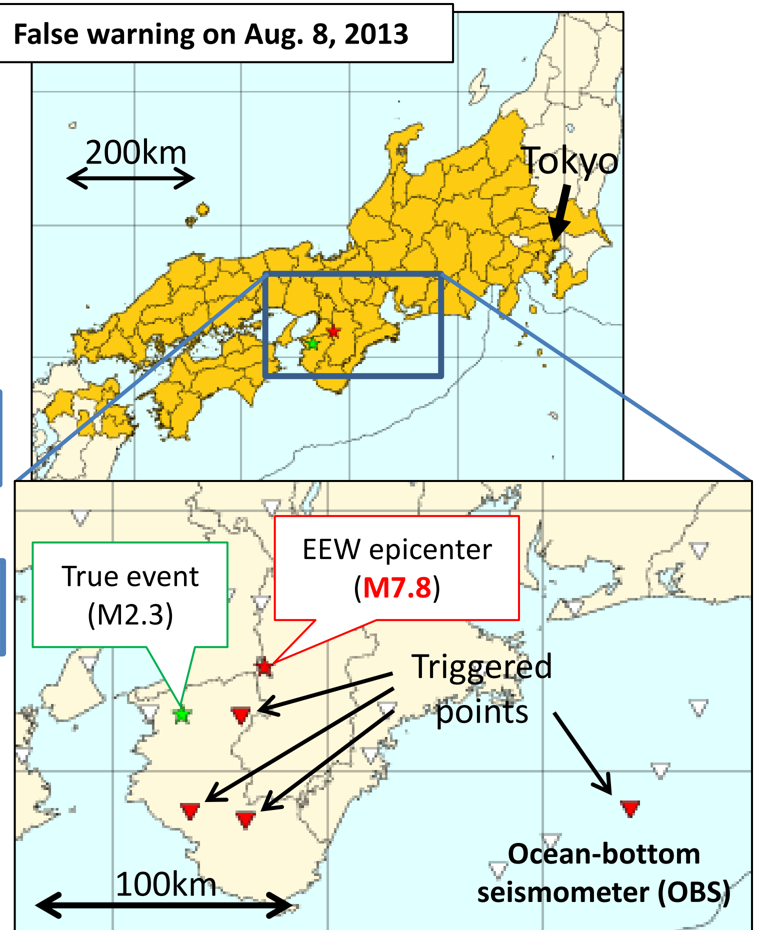
Observation







False warning on Aug. 8, 2013



3. What improvements are planned?

(1) Implementation of new methods

(2) Utilization of new seismometer networks

(1) Implementation of new methods

- IPF method

- PLUM method

- Hybrid method

Integrated Particle Filter (IPF) method

Tamaribuchi et al., 2014

A measure for (2) false alarms with active aftershock and noise data

Bayesian estimation

$$\underbrace{p(\theta\,|\,\mathbf{D})}_{\text{Posterior}} = \frac{\overbrace{p(\mathbf{D}\,|\,\theta)}^{\text{Likelihood}} \times \overbrace{p(\theta)}^{\text{Prior}}}{p(\mathbf{D})}$$

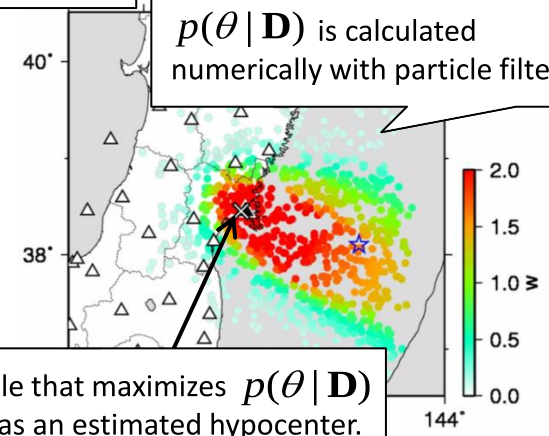
$\mathbf{D}$: Observations
θ : Hypocenter

Characteristic features:
- distance and direction of hypocenter (obtained from B-Δ and PCA)
- travel time
- magnitude

Past seismicity × Area constraint using Voronoi cell

Integrating various kinds of information makes hypocenter determination more robust.

Particle filter

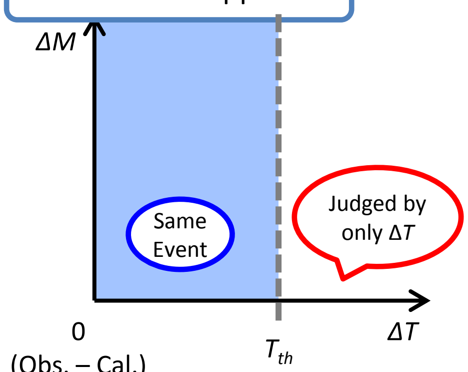


$p(\theta\,|\,\mathbf{D})$ is calculated numerically with particle filter.

The particle that maximizes $p(\theta\,|\,\mathbf{D})$ is chosen as an estimated hypocenter.

Earthquake identification logic in IPF method

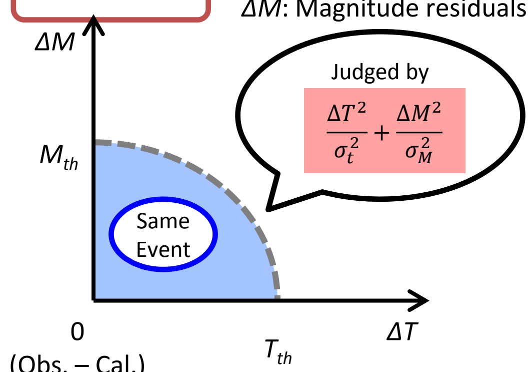
Conventional approach



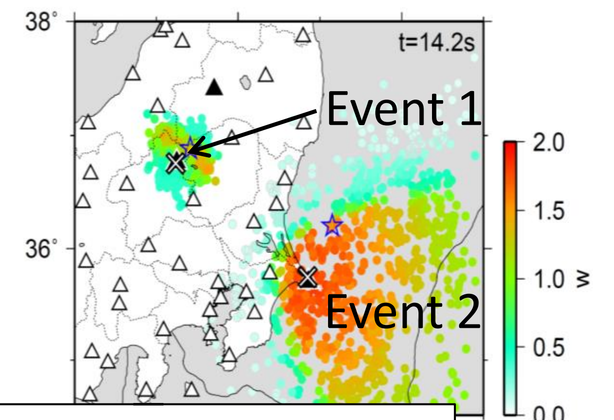
Only Arrival times are used.

IPF method

ΔT: Travel time residuals
ΔM: Magnitude residuals



Arrival times and Magnitude are used *integrally*.

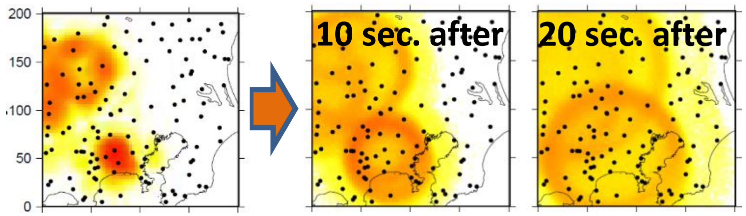


IPF method can separate simultaneous multiple earthquakes more easily using amplitude as well as travel time.

Propagation of Local Undamped Motion (PLUM) method

A measure for (1) under-prediction for huge earthquake

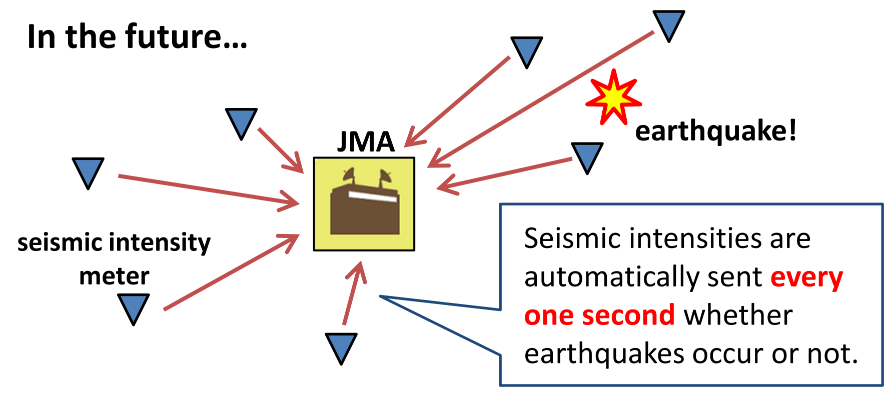
- A simplified version of **"numerical shake prediction"** (Hoshiba and Aoki, 2015)



- It predicts JMA seismic intensity **directly from real-time observed one**.

No need to determine hypocenter and magnitude!

Real-time JMA seismic intensity (Kunugi et al., 2008)



Calculation method

- **Assumption:**

  Strong motion propagates within 30km without attenuation.

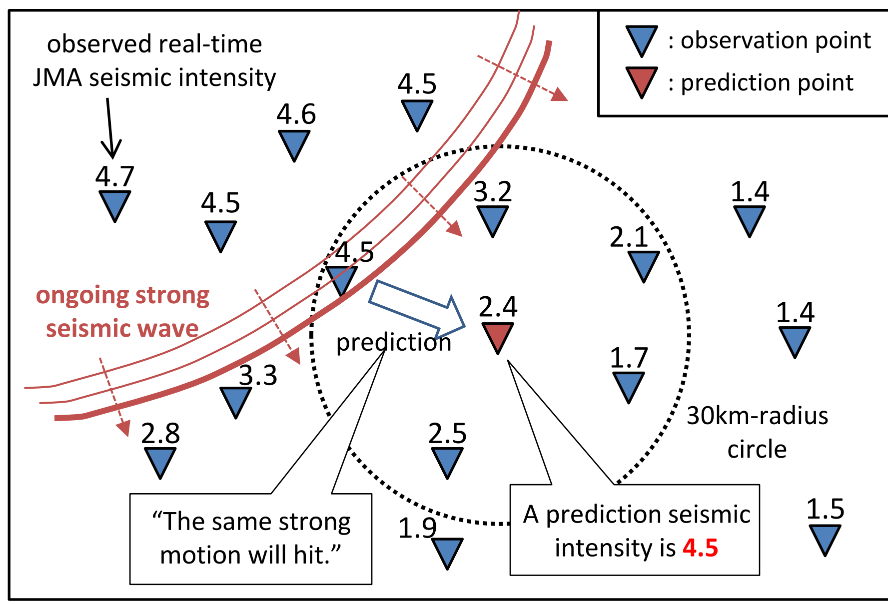
  an empirically determined value

- **Algorithm:**

  Collect observed real-time JMA seismic intensities within 30km at each prediction point

  Take the maximum value as a prediction of the target prediction point

  *In addition, values are corrected by site amplification factors.



Hybrid method

JMA plans to use IPF and PLUM method at the same time as “Hybrid method”.

It **gives long lead time** but **have difficulty with huge earthquake**.

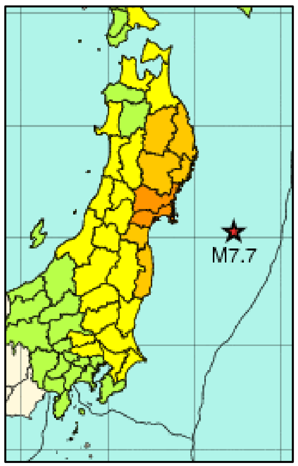
IPF method

It **gives short lead time** but **have no difficulty with huge earthquake**.

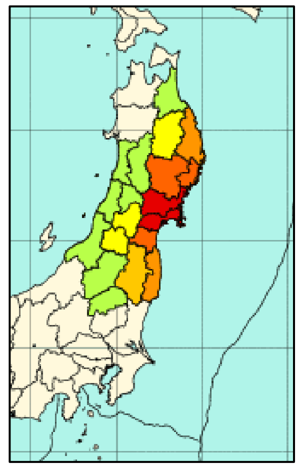
PLUM method

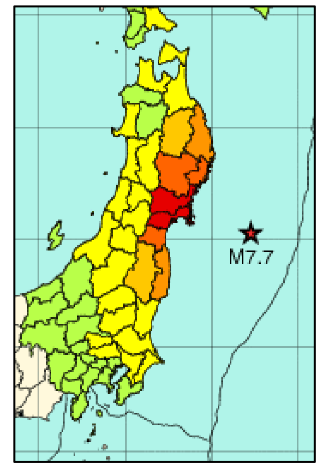
It **gives long lead time AND have no difficulty with huge earthquake**.

Hybrid method

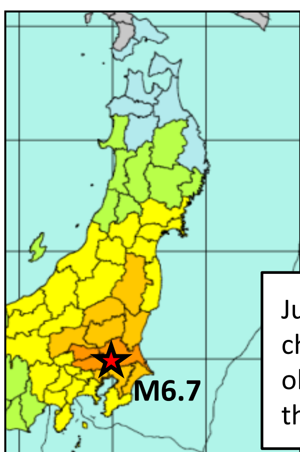


consistent



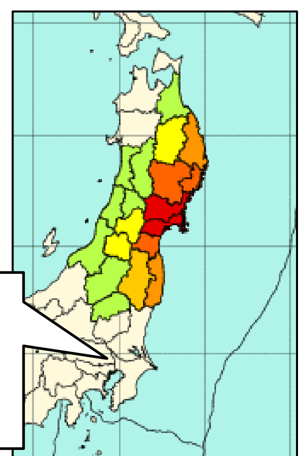


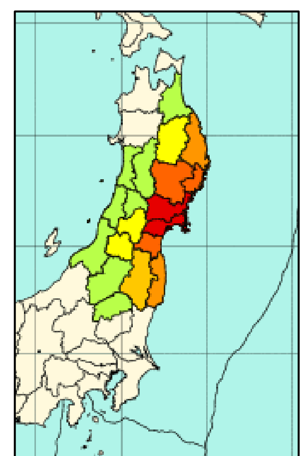
Take the maximum values when IPF and PLUM method are consistent.



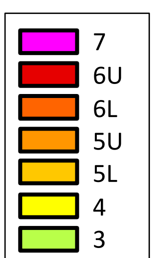
inconsistent

Judge consistency by checking real-time observation data near the estimated epicenter





Only take the values of PLUM method when IPF and PLUM method are inconsistent (to avoid a false alarm due to IPF method).



(2) Utilization of new seismometer networks

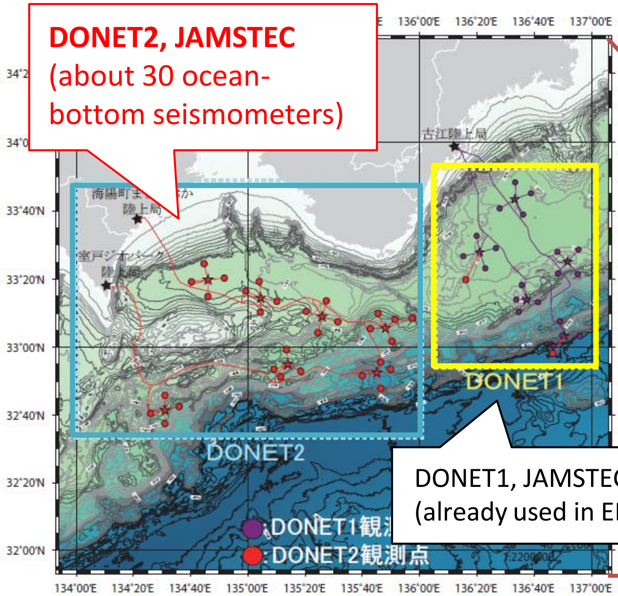
History of the number of seismometers used for the main part of the JMA EEW

	2007	2008	2009	2010	2011	2012	2013	2014	2015
Strong motion seismometer network, JMA	203 →	→	205 →	→	215 →	→	→	→	265
Ocean-bottom seismometer network, JMA			5 →	→	→	→	→	→	→
A part of KiK-net, NIED (deep borehole seismometers)									15
DONET1, JAMSTEC (ocean-bottom seismometers)									2

Many of additional seismometers are in islands or near the Pacific coast.

About 500- to 3000-meter depth seismometers around the Tokyo metropolitan area

Plans of additional utilization of new seismometer networks

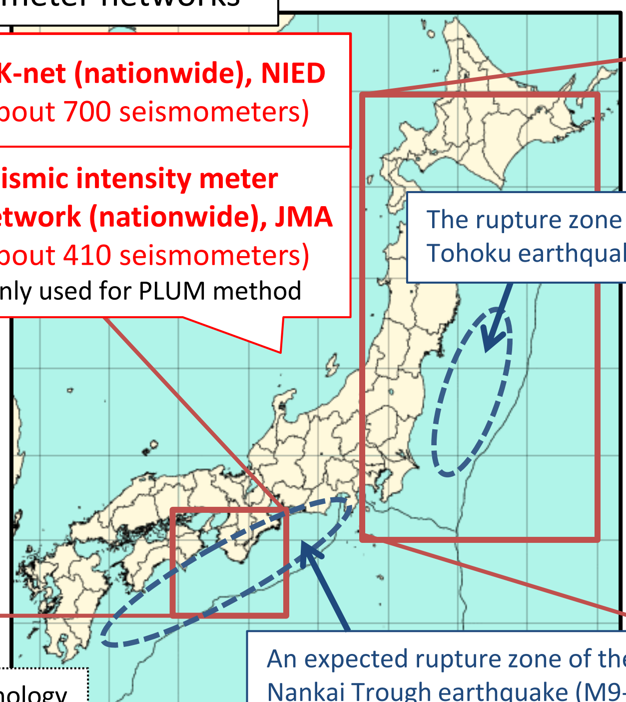


DONET2, JAMSTEC
(about 30 ocean-bottom seismometers)

DONET1, JAMSTEC
(already used in EEW)

https://www.jamstec.go.jp/donet/j/donet/donet2.html

*JAMSTEC: Japan Agency for Marine-Earth Science and Technology



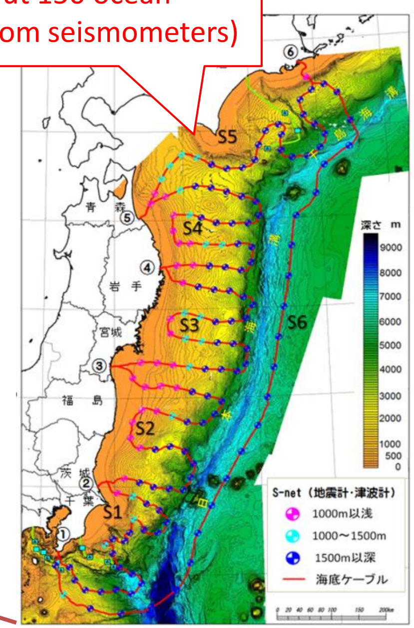
KiK-net (nationwide), NIED
(about 700 seismometers)

Seismic intensity meter network (nationwide), JMA
(about 410 seismometers)
*only used for PLUM method

The rupture zone of the Tohoku earthquake

An expected rupture zone of the Nankai Trough earthquake (M9-class)

S-net, NIED
(about 150 ocean-bottom seismometers)



http://www.bosai.go.jp/inline/seibi/seibi01.html

Summary

How does the JMA EEW work?

- It estimates hypocenter and magnitude and then predicts JMA seismic intensity.
- It selects appropriate calculation methods on moment-to-moment basis on hypocenter and magnitude estimation.
- It has helped with damage mitigation of real significant earthquakes.

What technical challenges have occurred during the operation?

(1) Under-prediction for huge earthquake
(2) False alarm with active aftershock and noise data

What Improvements are planned?

- Implementation of IPF method, which includes Bayesian estimation and particle filter, to distinguish simultaneous multiple earthquakes and noise data properly
- Implementation of PLUM method, which predicts JMA seismic intensity directly from real-time observed one, to predict appropriate strong motions of huge earthquakes
- Implementation of Hybrid method, which combines IPF and PLUM method
- Utilization of new seismometer networks including large-scale OBS networks and denser inland seismometer networks

Acknowledgments

- The JMA EEW system is based on joint research with JMA and the Railway Technical Research Institute and technological achievements by the National Research Institute for Earth Science and Disaster Prevention (NIED).
- Seismic intensity and waveform data are obtained from the JMA network, K-NET of NIED and local governments and municipals.