ISTITUZIONI DI FISICA
PER IL SISTEMA TERRA

TSUNAMI

FABIO ROMANELLI

Department of Mathematics & Geosciences

University of Trieste

romanel@units.it

http://moodle2.units.it/course/view.php?id=9059

Gravity waves: dispersion

From the expression

$$F(z) = 2Ae^{-kh} \cosh\left[k(z+h) \right]$$

the boundary at the top gives the dispersion relation for incompressible, irrotational, small amplitude "gravity" waves:

$$\omega^2 = kg\left[\tanh(kh) \right]$$

Deep water
(kh goes to infinity)

$$\omega^2 = kg$$

$$c = \sqrt{\frac{g}{k}} = \sqrt{\frac{g\lambda}{2\pi}}$$

$$u = \frac{\partial \omega}{\partial k} = \frac{1}{2}\sqrt{\frac{g}{k}} = \frac{1}{2}\sqrt{\frac{g\lambda}{2\pi}} = \frac{1}{2}c$$
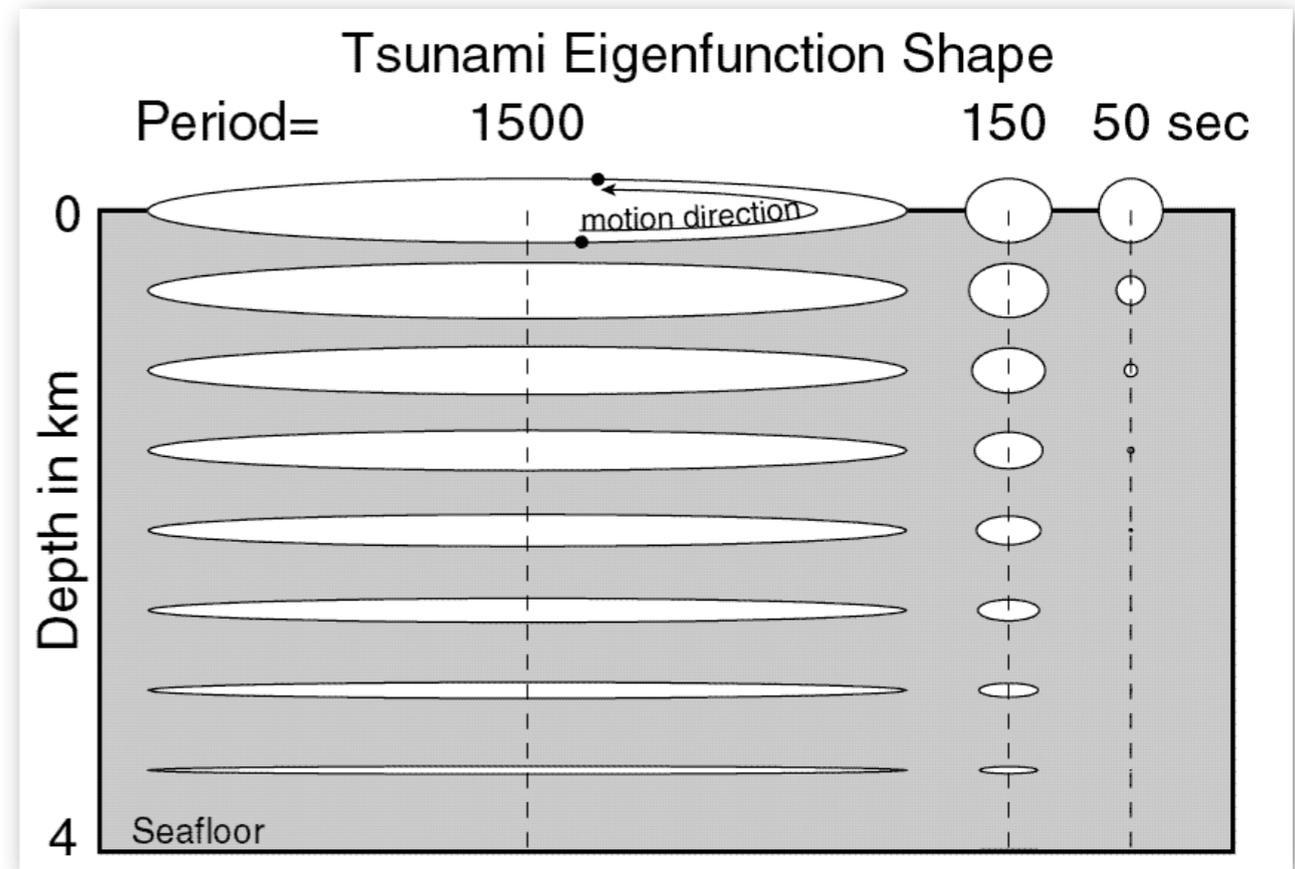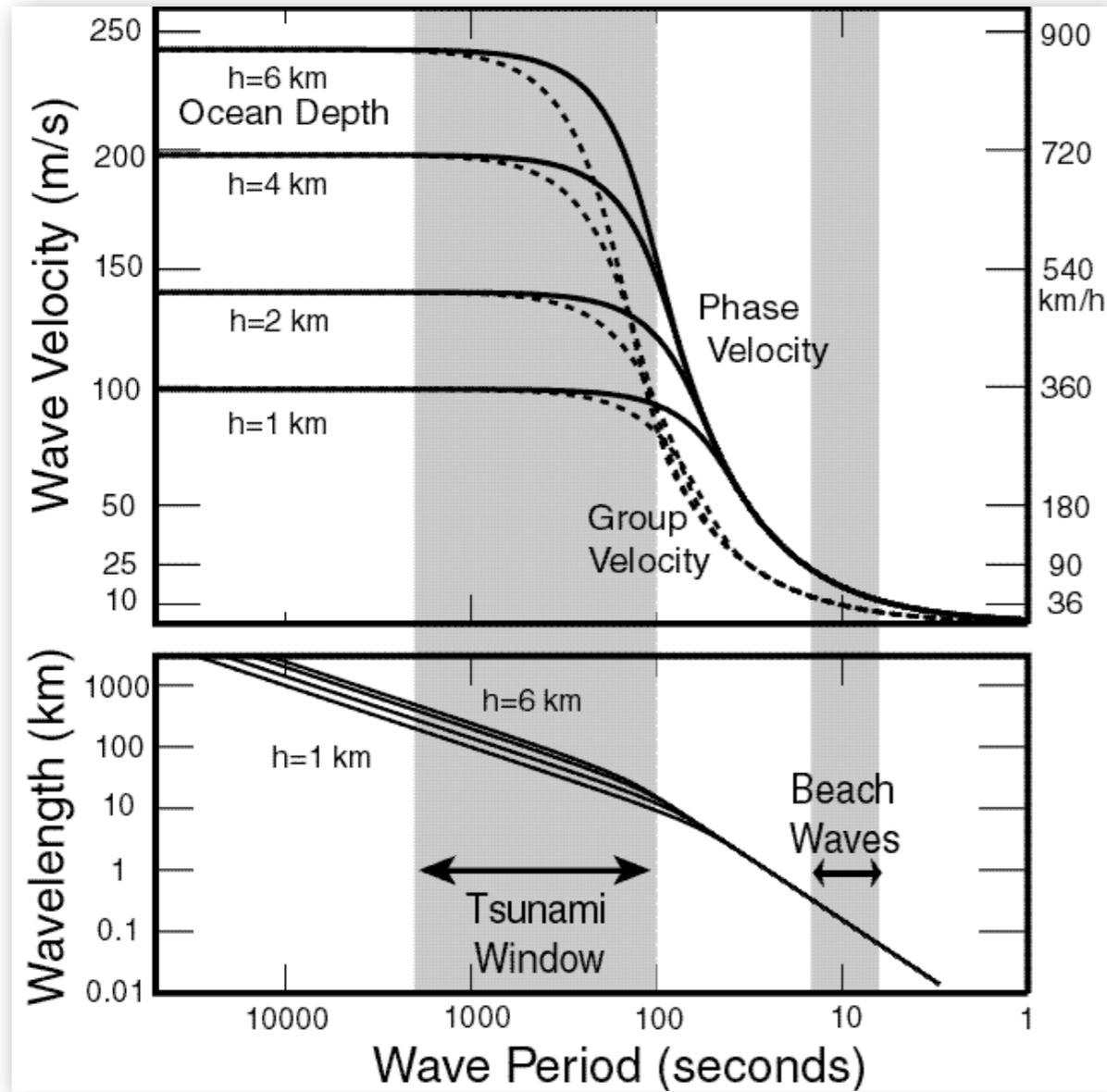
Shallow water
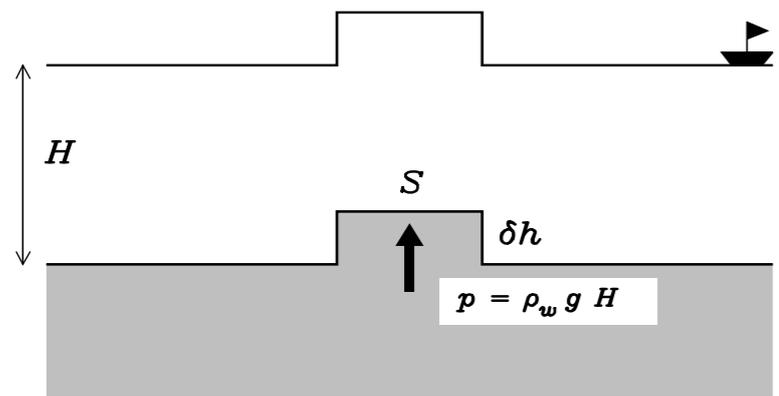(kh goes to zero)

$$\omega^2 = k^2 gh$$

$$c = \sqrt{gh}$$

$$u = \frac{\partial \omega}{\partial k} = c = \sqrt{gh}$$

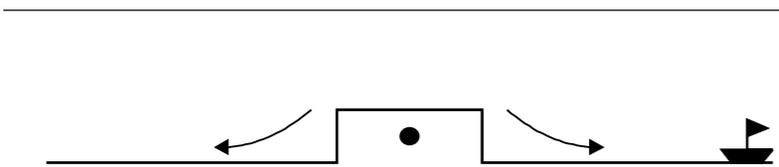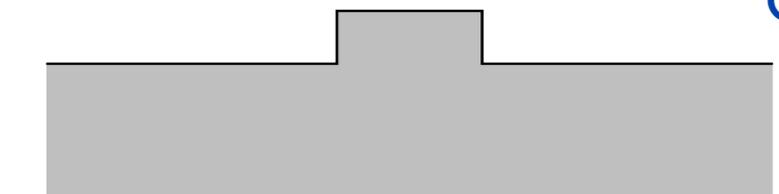# Tsunami eigenvalues & eigenfunctions

$$\omega^2 = gk(\omega)\tanh[k(\omega)h]$$
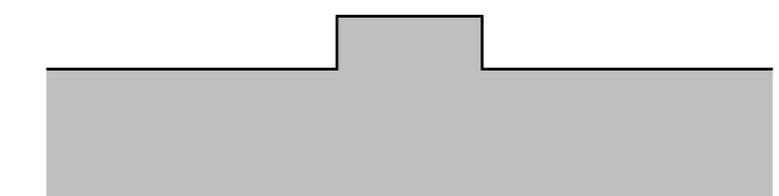
Very basic tsunami physics...

Bottom uplift & Waterberg formation

Center of mass falls...

Potential energy goes to tsunami energy

Energy

$$\log E_R \approx 5.0 + 1.5M$$

$$E_T = \frac{1}{2}\rho g L \lambda (\delta h)^2$$

$$L \sim 10^6 \text{m}; \ \lambda \sim 10^4 \text{m}; \ \delta h \sim 5\text{m}$$
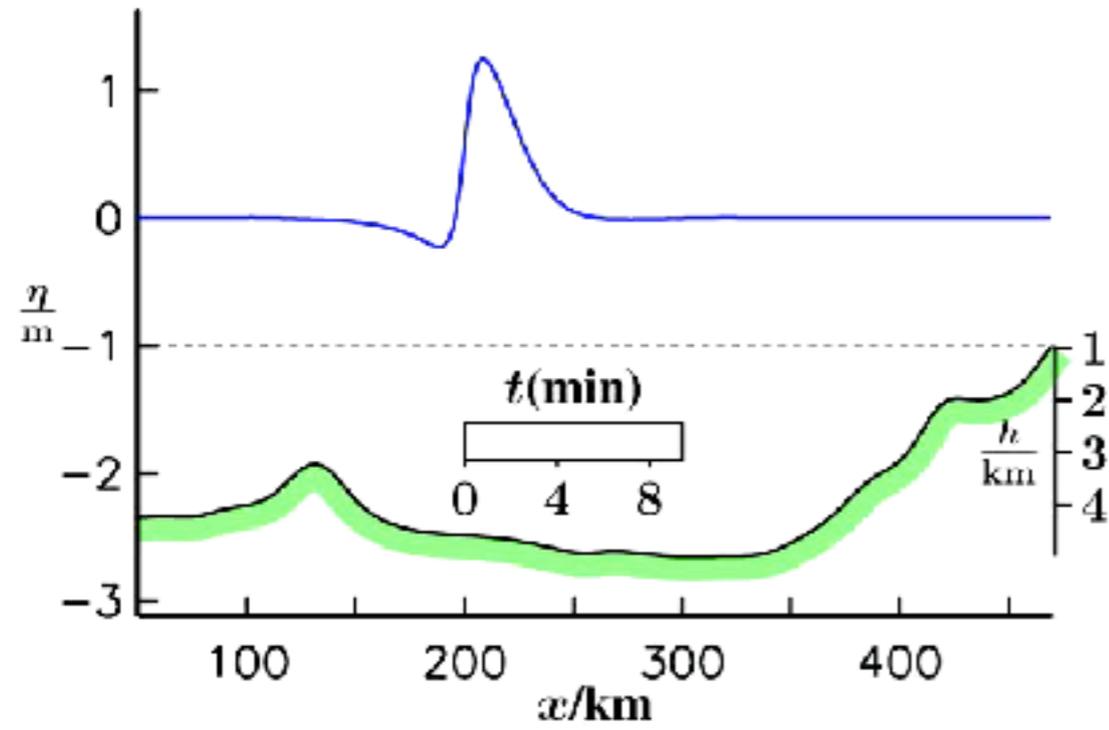
$$E_R \approx 10^{18}\text{j} \geq 10^2 E_T$$

Wavelength

$$\frac{\lambda}{H} \sim 40 \ ; \ \frac{H}{a} \sim 3 \cdot 10^3$$

$$\lambda \gg H \gg a$$

Tsunami is a shallow-water gravity wave with great wavelength and tiny amplitude

DISPERSION

$\frac{\eta}{m}$

$t(min)$

0 4 8

$\frac{h}{km}$

x/km

DISPERSION, AMPLIFICATION

$\frac{\eta}{m}$

$t(min)$

10 20 30

$\frac{h}{km}$

x/km

AMPLIFICATION

$\frac{\eta}{m}$

$t(min)$

30 40 50

$\frac{h}{m}$

x/km

BORE FORMATION

$\frac{\eta}{m}$

$t(min)$

45 50 55 60

$\frac{h}{m}$

x/km

Tsunami physics research

- support of improved measurement technology and the design of optimal **tsunami monitoring networks**

- implementation of improved models to increase the speed and accuracy of operational **forecasts and warnings**

- development of improved methods to **predict tsunami impacts** on the population and infrastructure of coastal communities
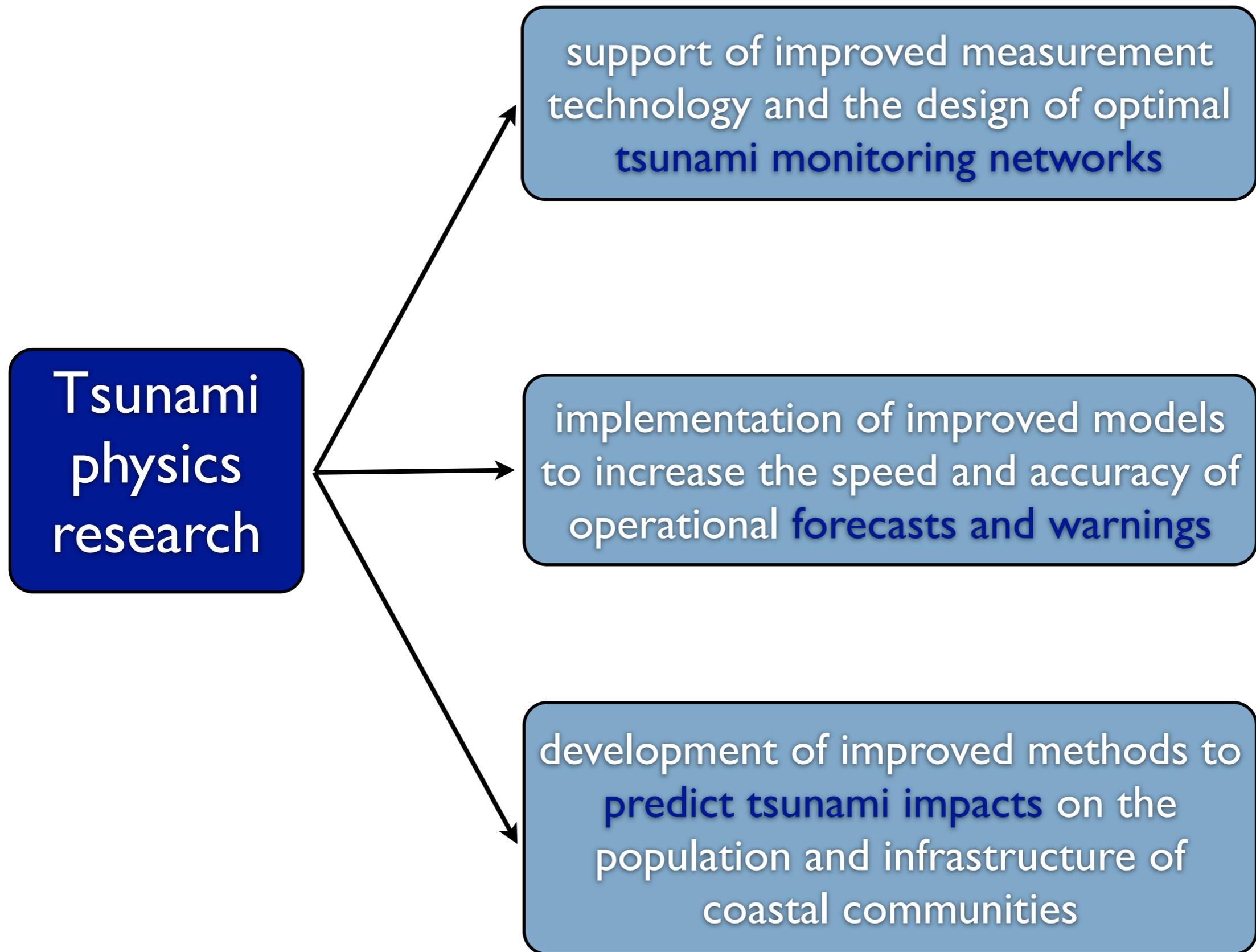
Tsunami forecast model

Generation of a database of pre-computed scenarios from potential sources

Arrival time
Height
Inundation area

Inundation modelling

Inundation maps

maximum wave height and maximum current speed as a function of location, maximum inundation line, as well as time series of wave height at different locations indicating wave arrival time

December 26, 2004 Indonesia (Sumatra) - Global tsunami propagation
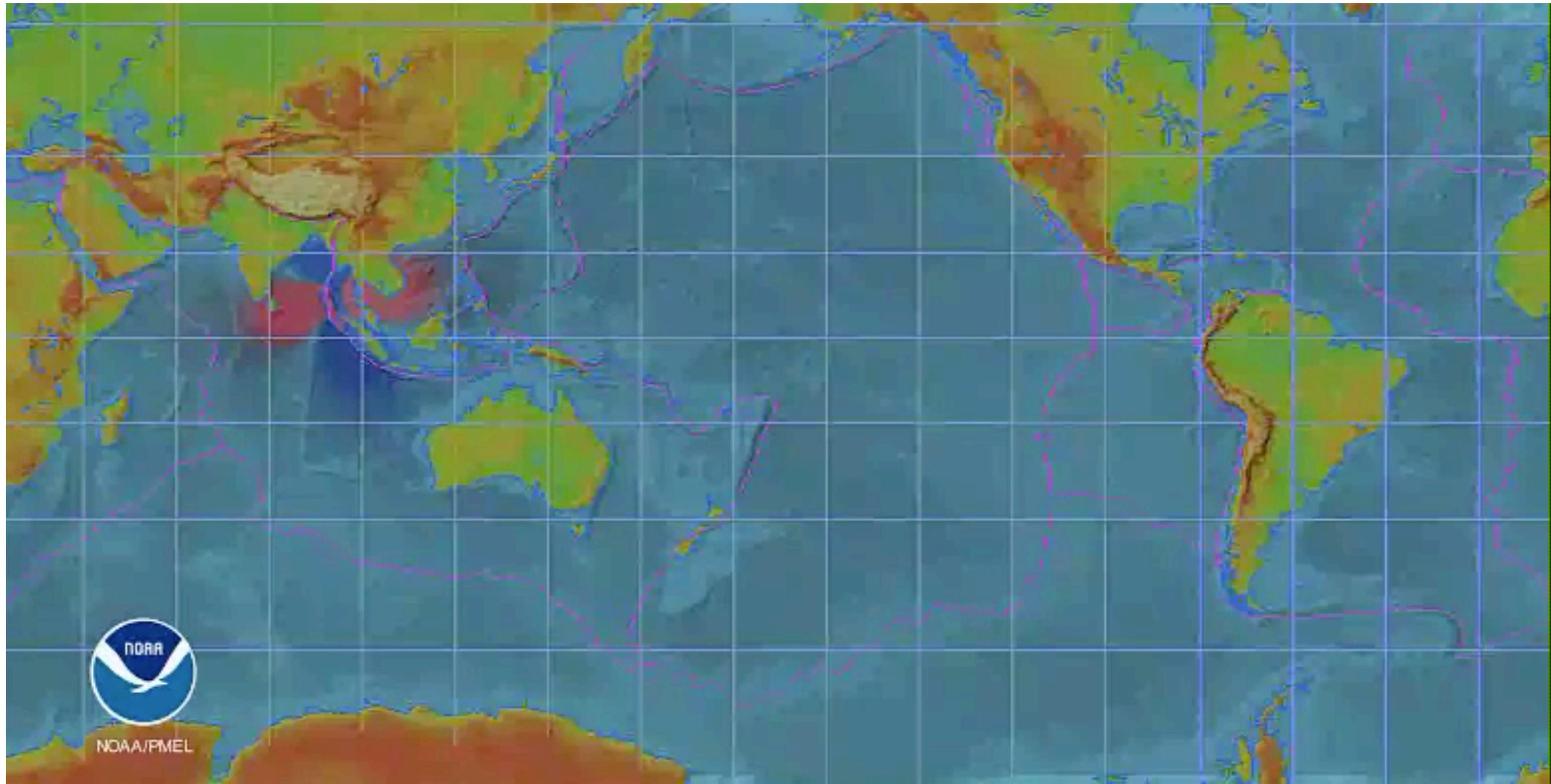
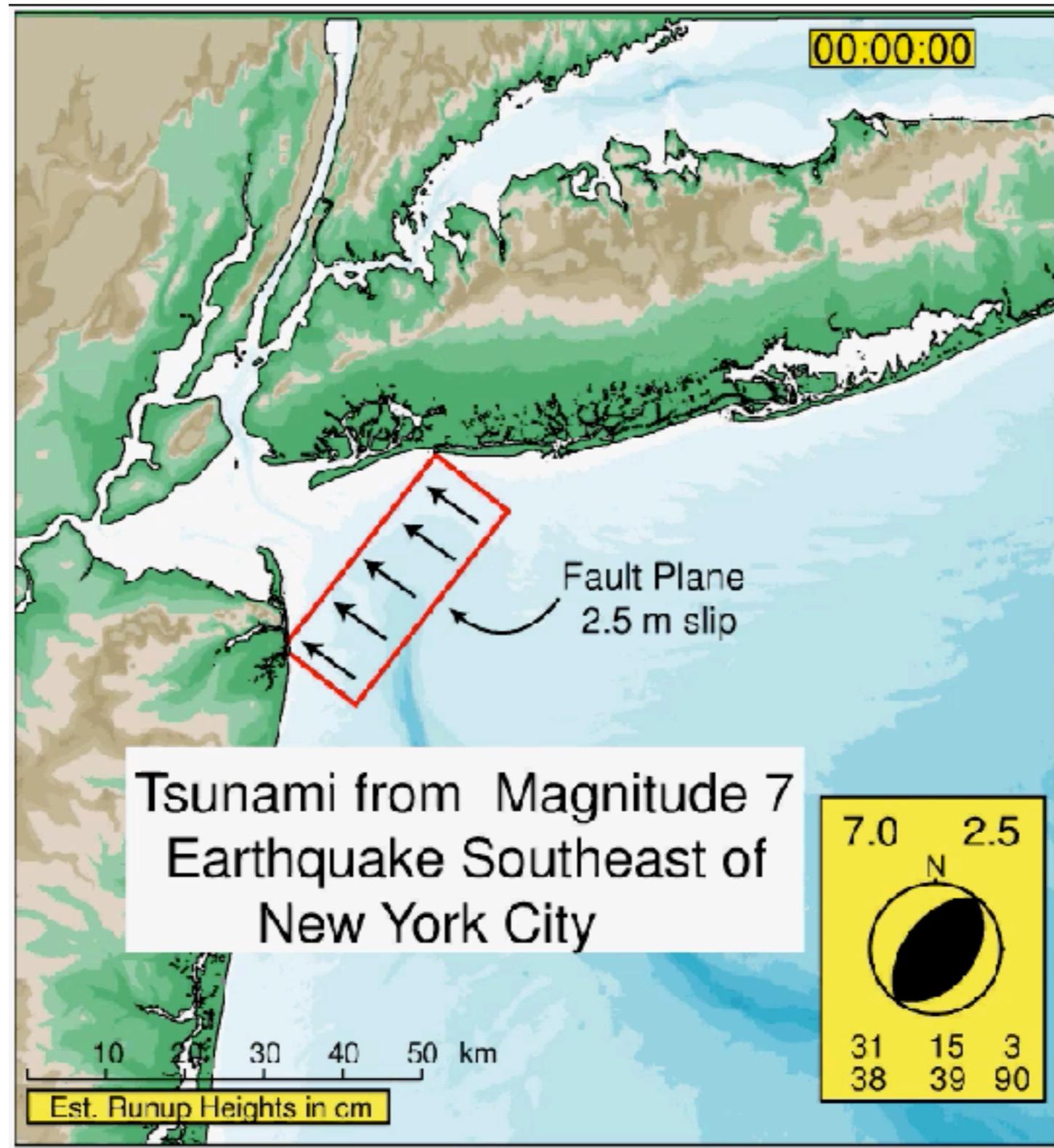Inundation of the Aonae peninsula during the July 12, 1993 Hokkaido-Nansei-Oki tsunami computed with the MOST inundation model.

http://nctr.pmel.noaa.gov/model.html
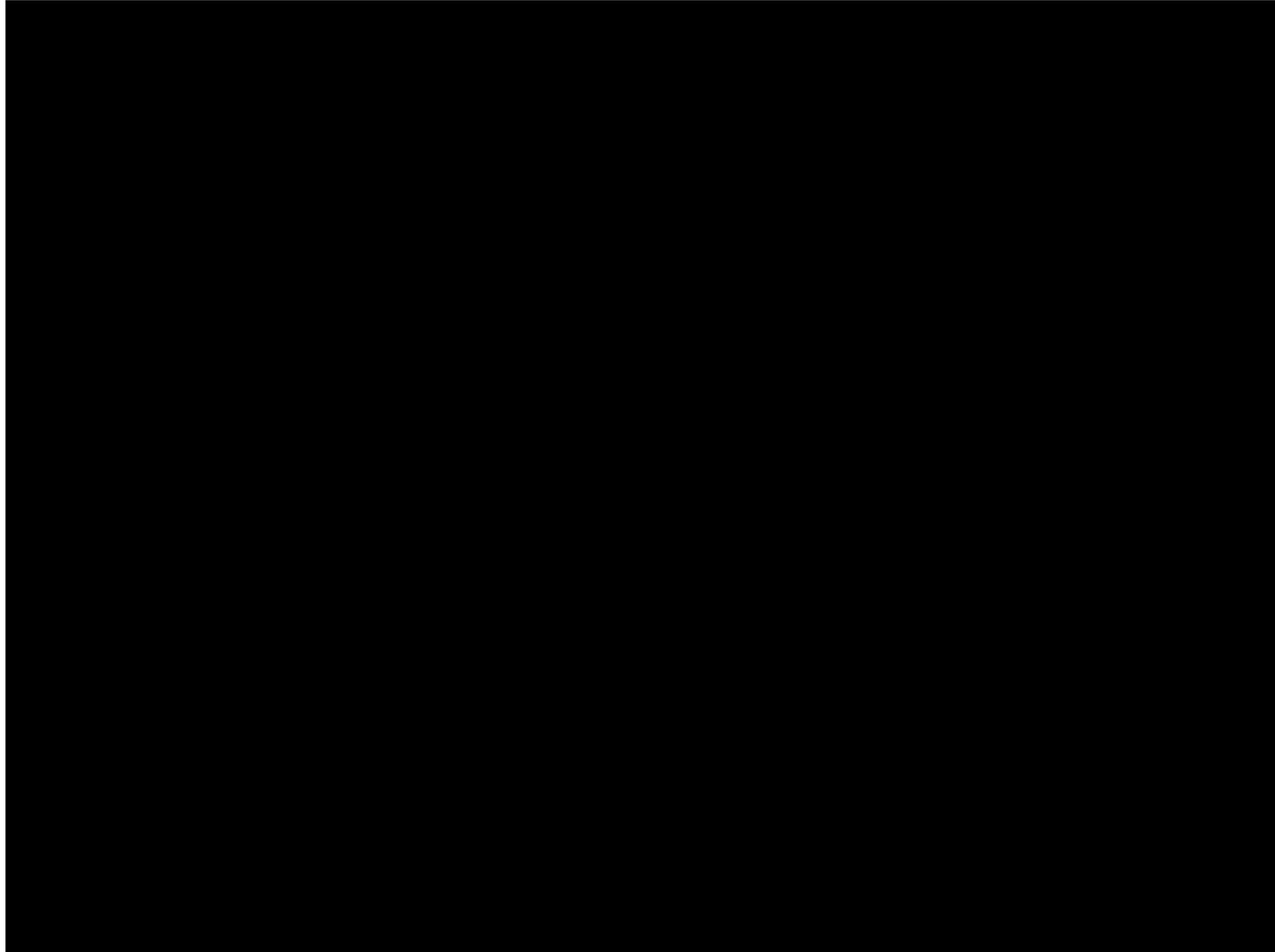
New York City Tsunami from M7 Quake

Courtesy of Steven Ward: http://www.es.ucsc.edu/~ward/

Atlantic Ocean Asteroid Tsunami Simulation - 3d

00:00:00   0   1000   2000 km

Courtesy of Steven Ward: http://www.es.ucsc.edu/~ward/
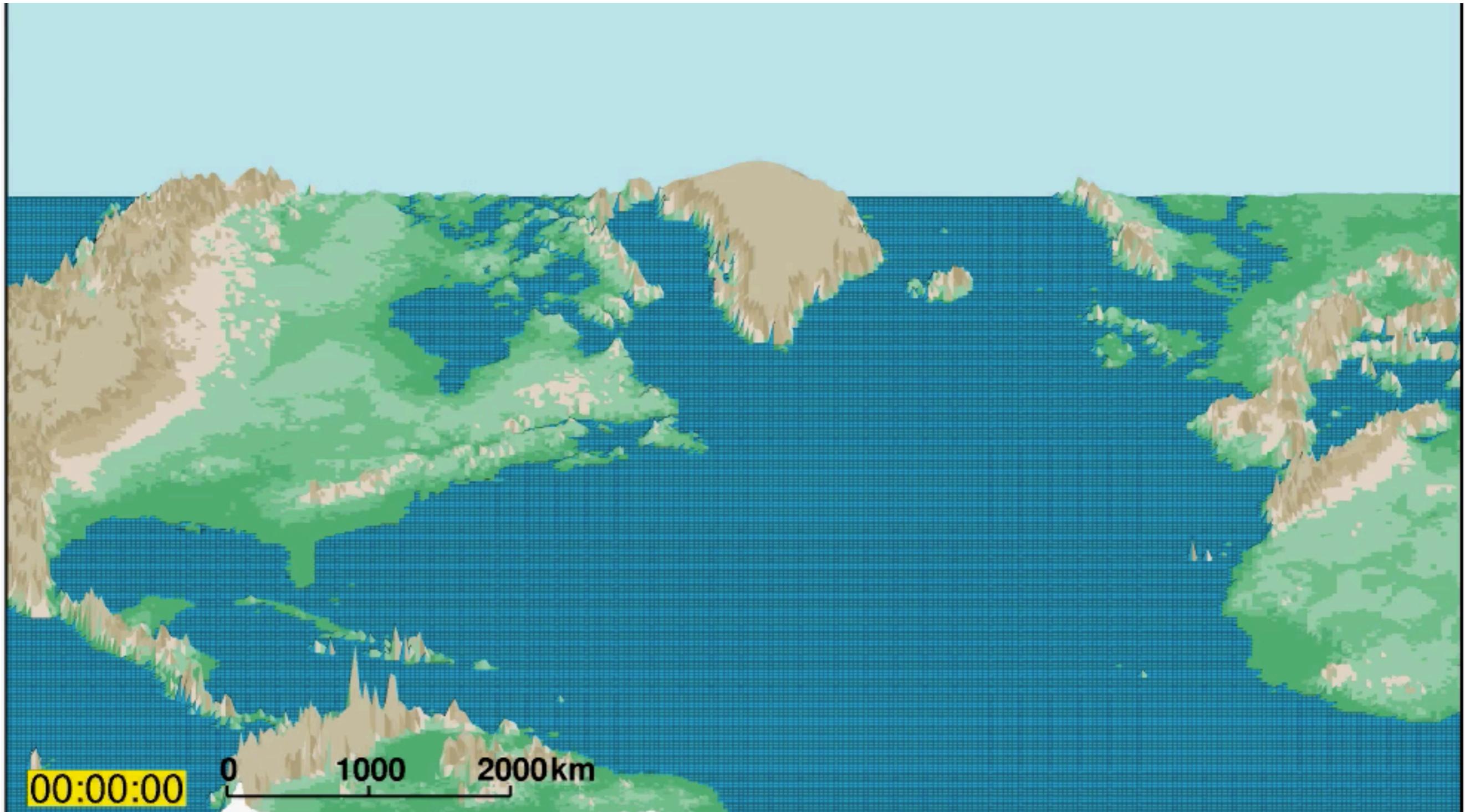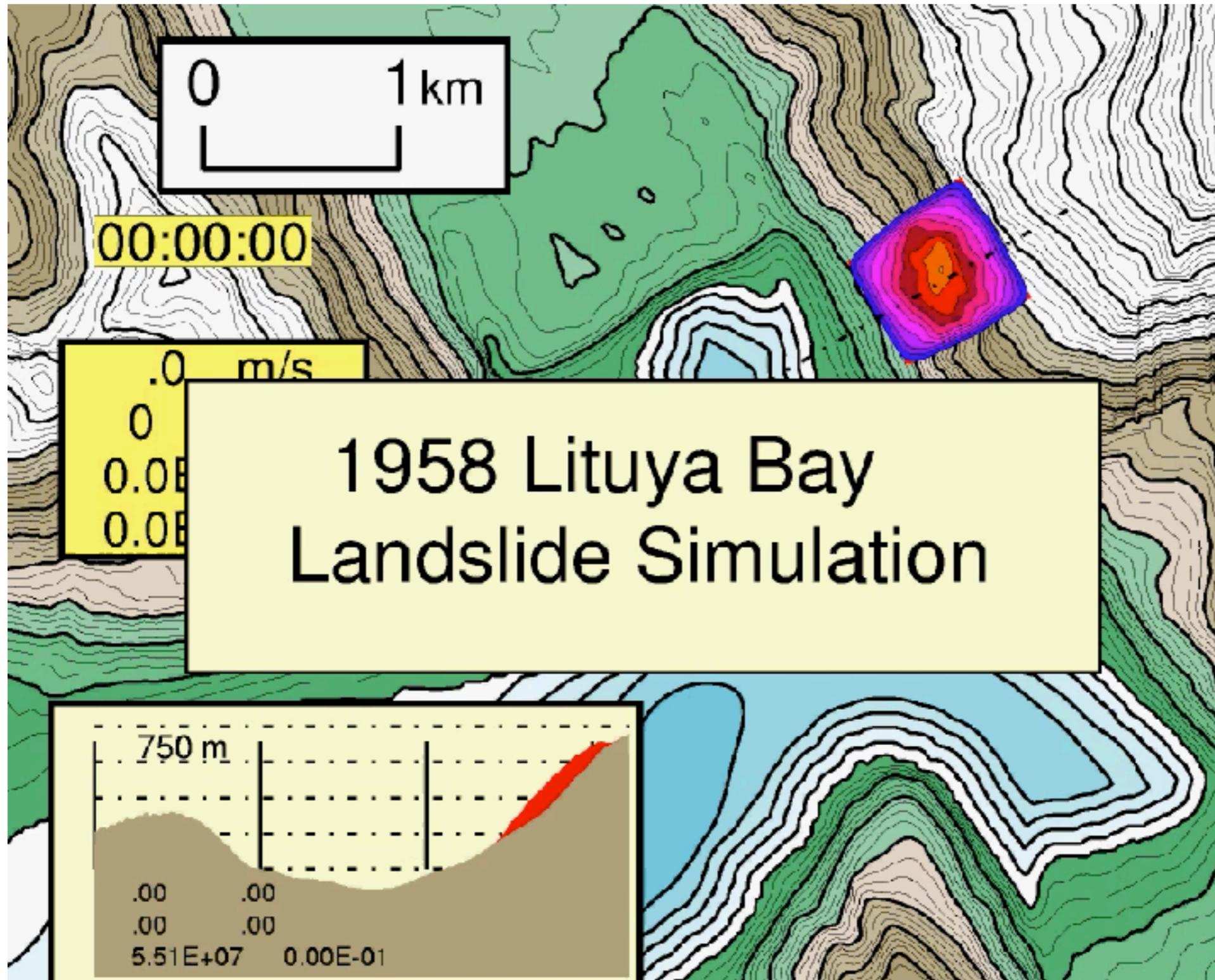
1958 Lituya Bay Landslide

Courtesy of Steven Ward: http://www.es.ucsc.edu/~ward/

1958 Lituya Bay Landslide
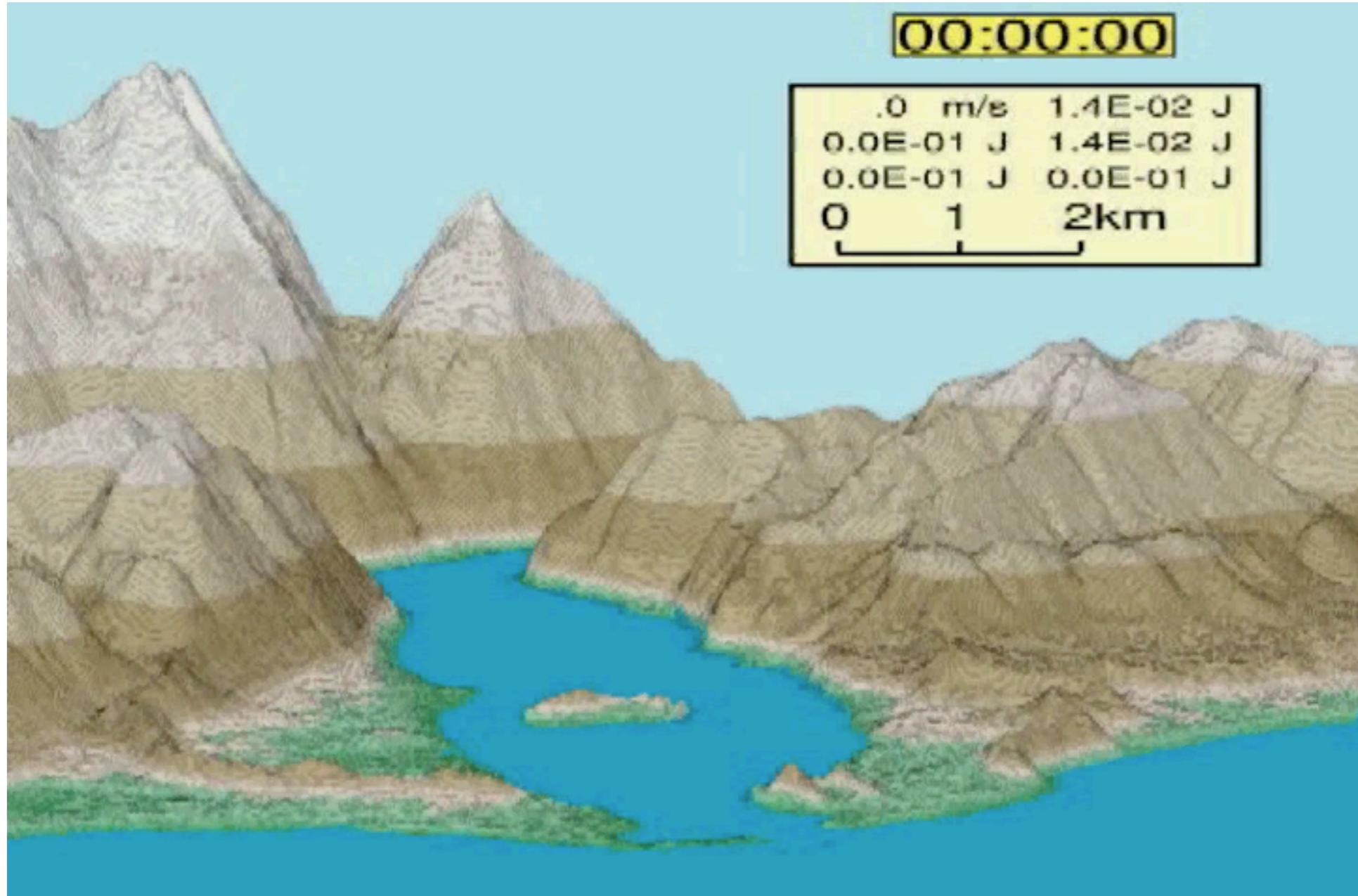
Santorini Tsunami Simulation 3D

Ocean bottom data

The observation record of the ocean bottom pressure gauge. At around 14:46, the ground motion of the earthquake (M9) reaches the pressure gauge and at TM1 (coast-side), the sea level is gradually rising from that point.

The sea level rose 2 m, and after 11 minutes, the level went drastically up to 3m, which makes 5 m of elevation in total. At TM2: located 30km toward the land, a same elevation of sea level was recorded with 4 minutes delay from TM1.
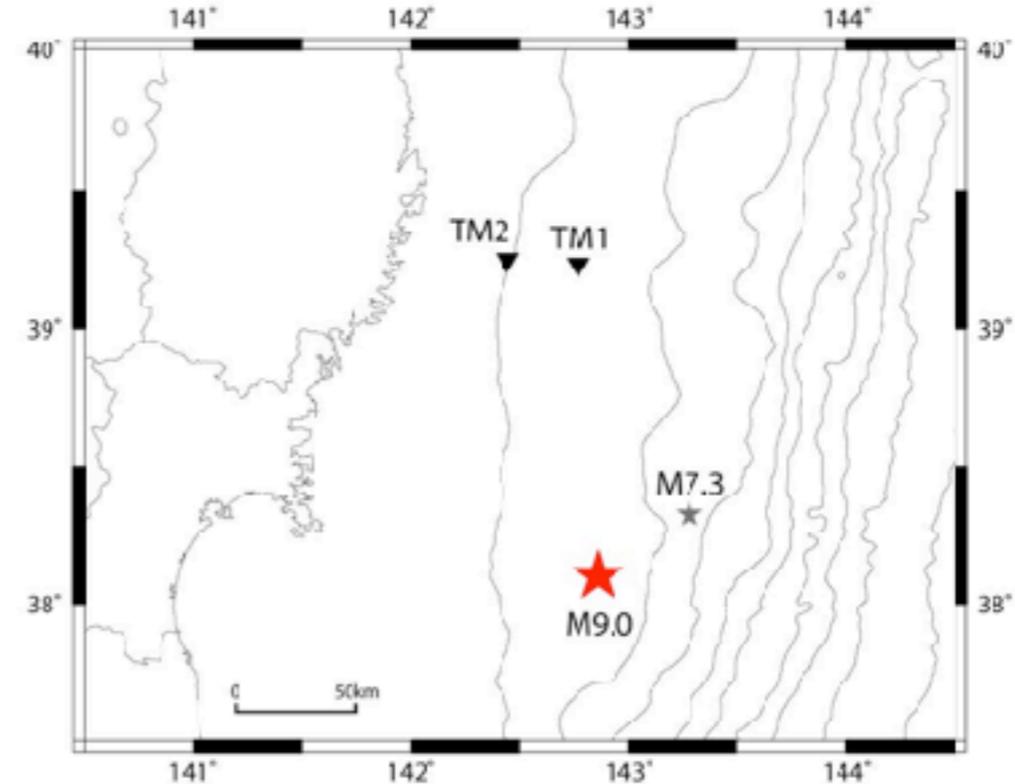
釜石沖海底ケーブル式地震計システムで観測された海面変動
東京大学地震研究所

図1　釜石沖ケーブル式海底水圧計の位置

波高(m)
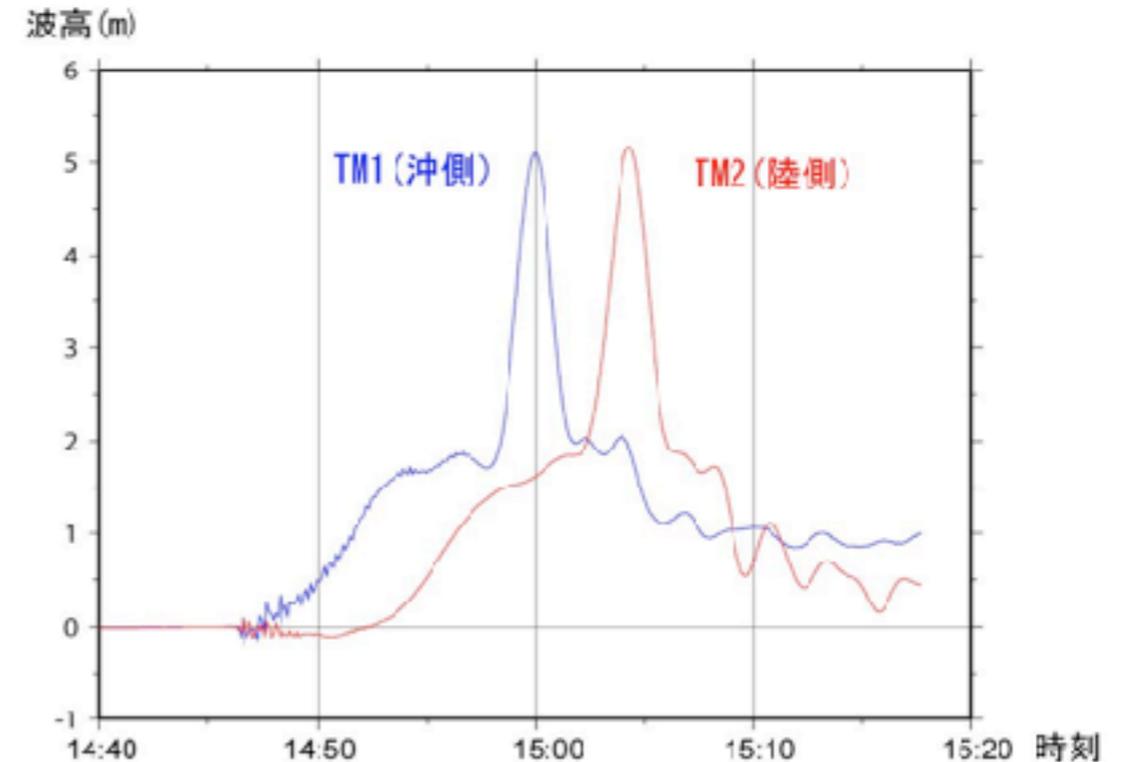
図2　海底水圧計の観測記録。14時46分頃、本震(M9.0)の振動が水圧計に伝わり、TM1(海寄り)では、その時から徐々に海面が上昇している。約2m上昇し、約11分後にはさらに約3m急激に上昇し、合計約5m海面が上昇した。約30km陸寄りに設置されているTM2では、TM1から約4分遅れて同様の海面上昇を記録した。

Dart buoys
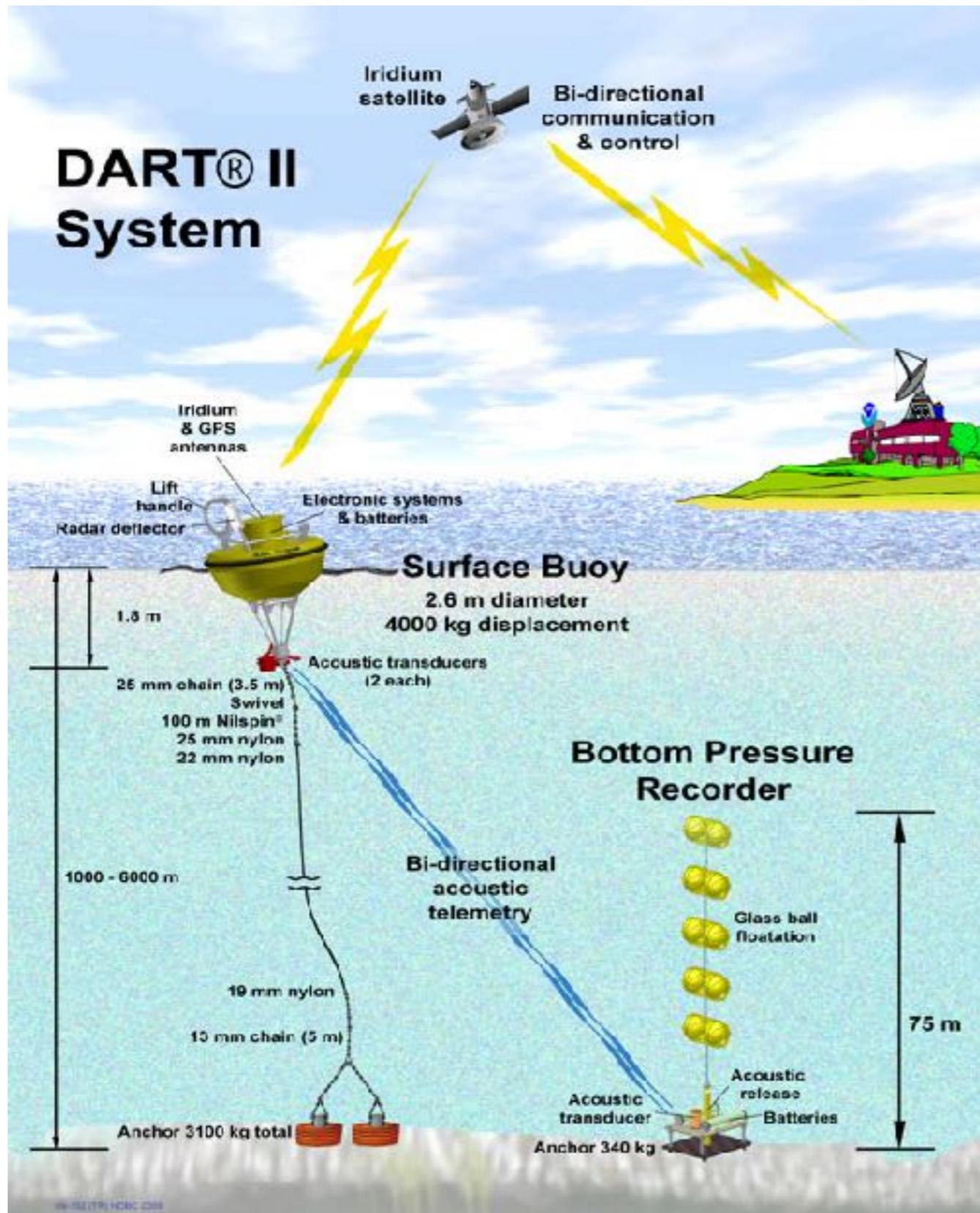
The DART II® system consists of a seafloor bottom pressure recording (BPR) system capable of detecting tsunamis as small as 1 cm, and a moored surface buoy for real-time communications.

DART II has two-way communications between the BPR and the Tsunami Warning Center (TWC) using the Iridium commercial satellite communications system. The two-way communications allow the TWCs to set stations in event mode in anticipation of possible tsunamis or retrieve the high-resolution (15-s intervals) data in one-hour blocks for detailed analysis.

DART II systems transmit standard mode data, containing twenty-four estimated sea-level height observations at 15-minute intervals, once very six hours.

NOAA

Tsunami data and simulations: source

2011 off the Pacific coast of Tohoku earthquake 0001 min
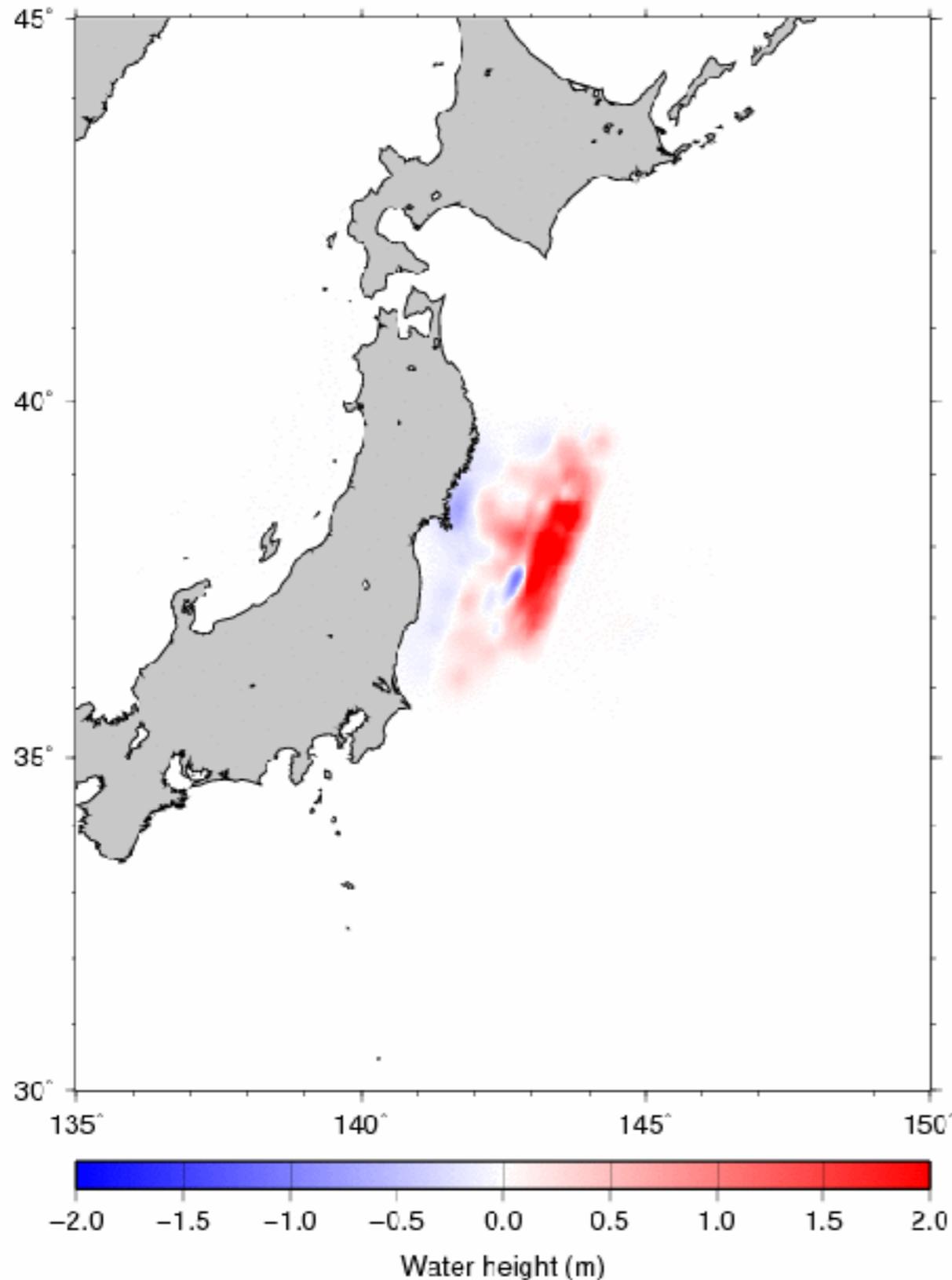
Tsunami Propagation
The red color means that the water surface is higher than normal sea level, while the blue means lower.

Tsunami data and simulations

2011 Off Tohoku–Pacific Earthquake

Tsunami data and simulations: source

Simulated Tsunami around Japanese coasts

Red and blue lines indicate the observed tsunami waveforms at Japanese tide gauges and ocean bottom tsunami sensors and synthetic ones, respectively. Solid lines show the time windows used for inversion.

Tsunami data and simulations: source
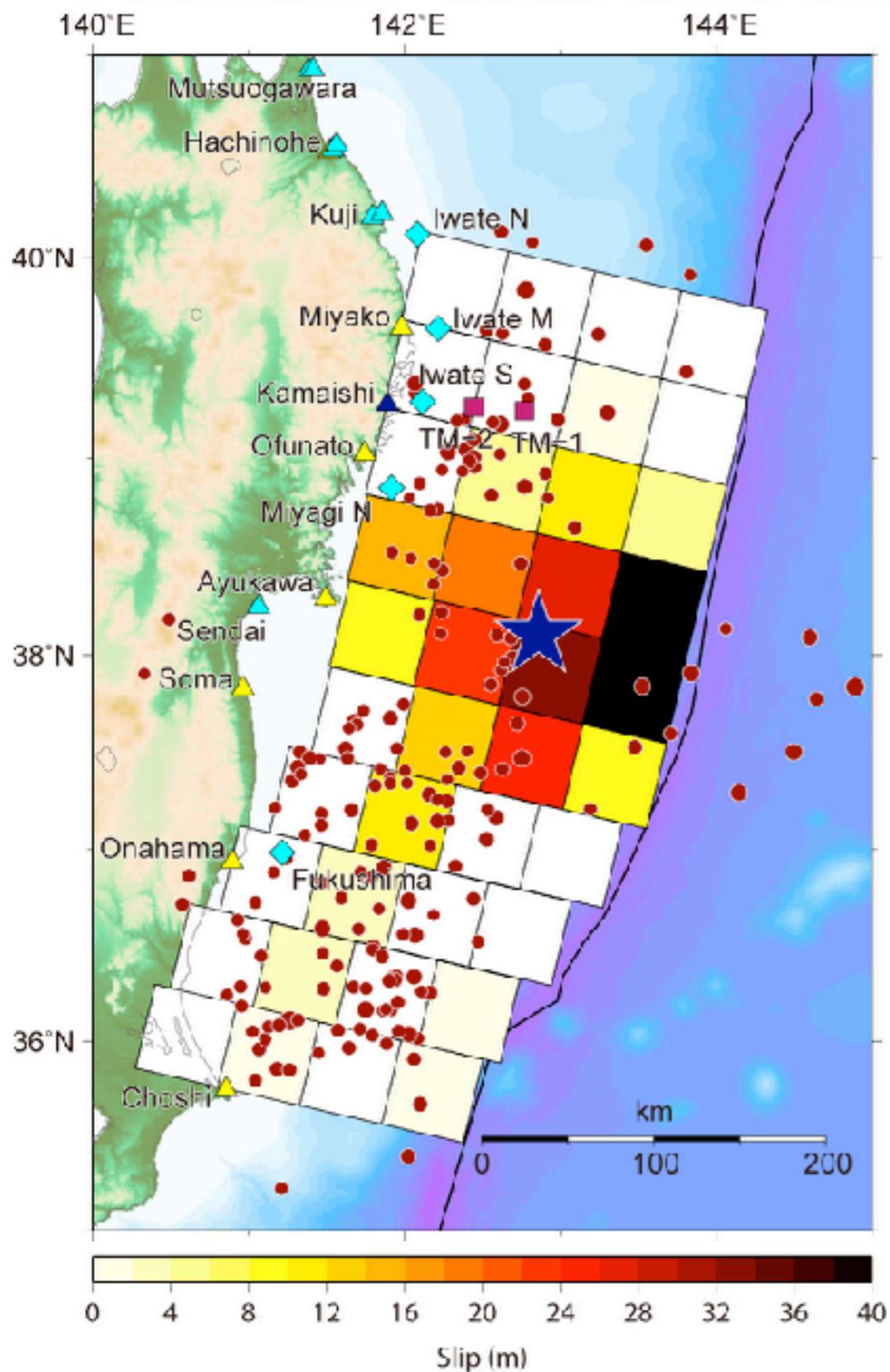
Slip distribution on the fault mode
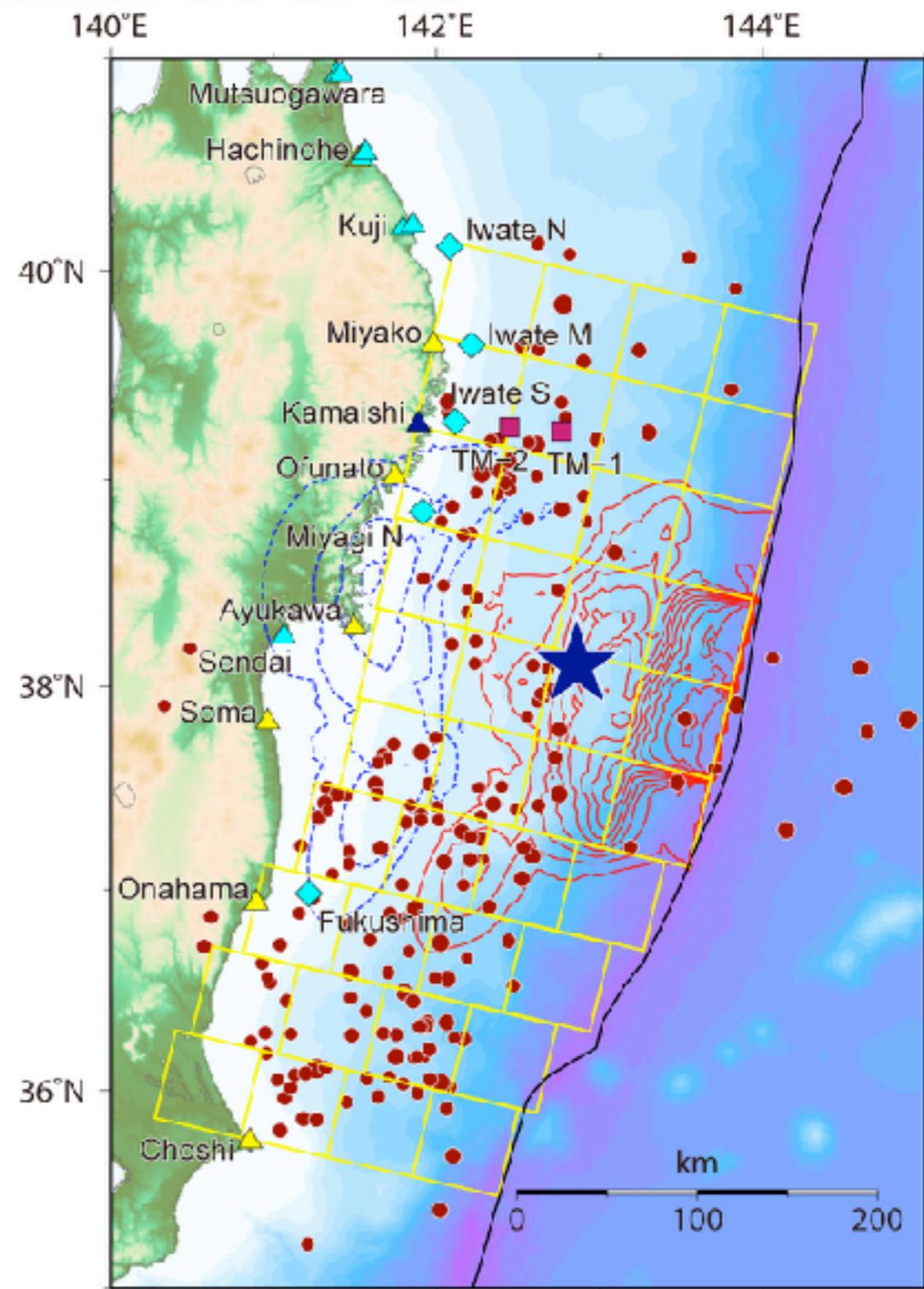
Calculated seafloor deformation due to the fault model

by Yushiro Fujii (IISEE, BRI) and Kenji Satake (ERI, Univ. of Tokyo)
http://iisee.kenken.go.jp/staff/fujii/OffTohokuPacific2011/tsunami_inv.html

Distribution of tsunami heights (upd)
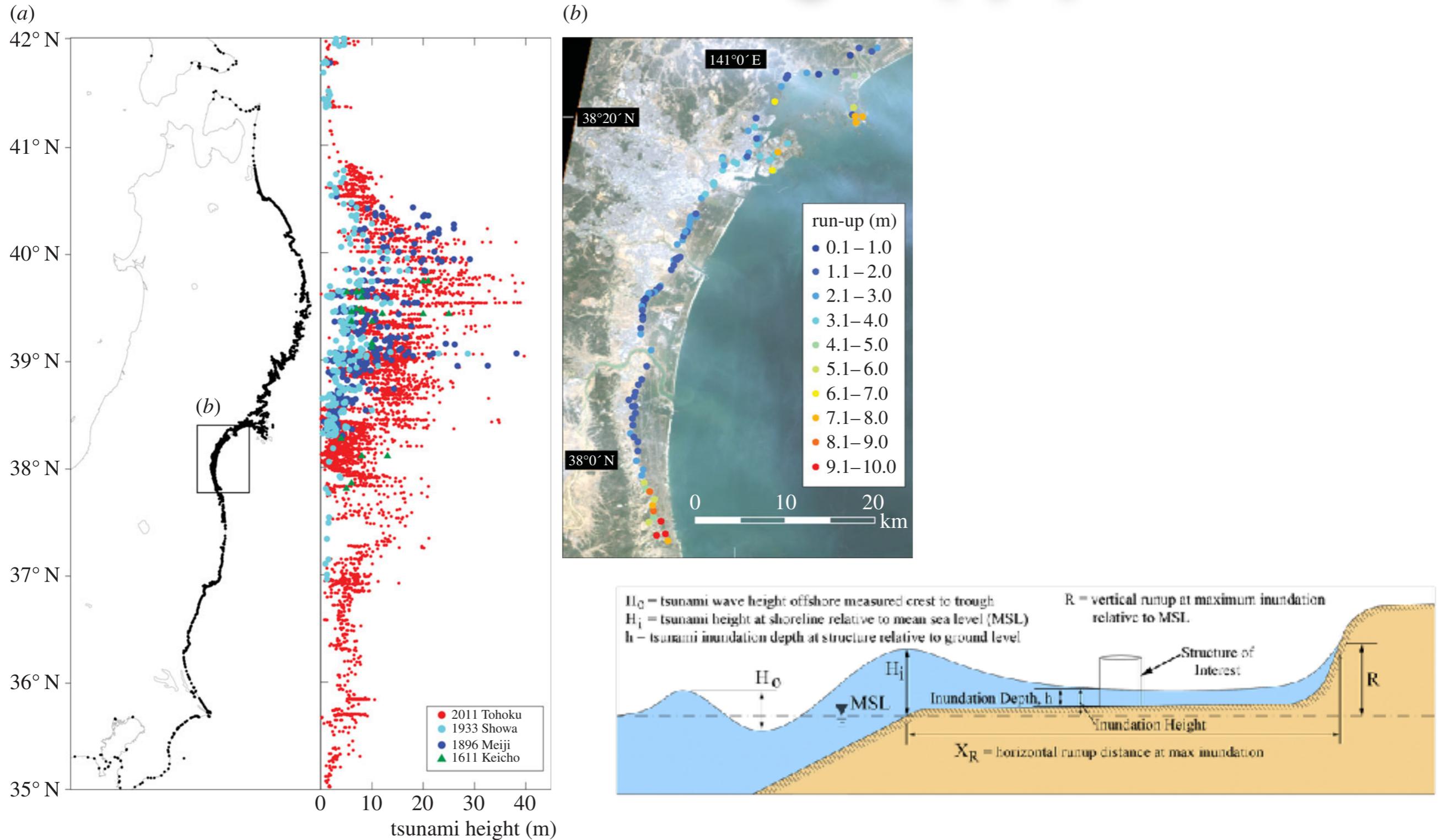
Figure 2. (a) The measured heights of the 2011 Tohoku tsunami [22] and historical Sanriku earthquake tsunamis (1611, 1896 and 1933 events). The historical tsunami data were provided by Japan Tsunami Trace Database [24] maintained by Tohoku University and the Japan Nuclear Energy Safety Organization (JNES). Black dots on the coastline indicate the points of the 2011 tsunami height measurement. The tsunami run-up height reached up to 40 m in Iwate prefecture. (b) The extent of the tsunami inundation zone with the measurement of the run-up heights at tsunami inundation limit in Sendai Coast [23].

Tsunami animation: time scales...

http://outreach.eri.u-tokyo.ac.jp/eqvolc/201103_tohoku/eng/

http://supersites.earthobservations.org/honshu.php

http://eqseis.geosc.psu.edu/~cammon/Japan2011EQ/
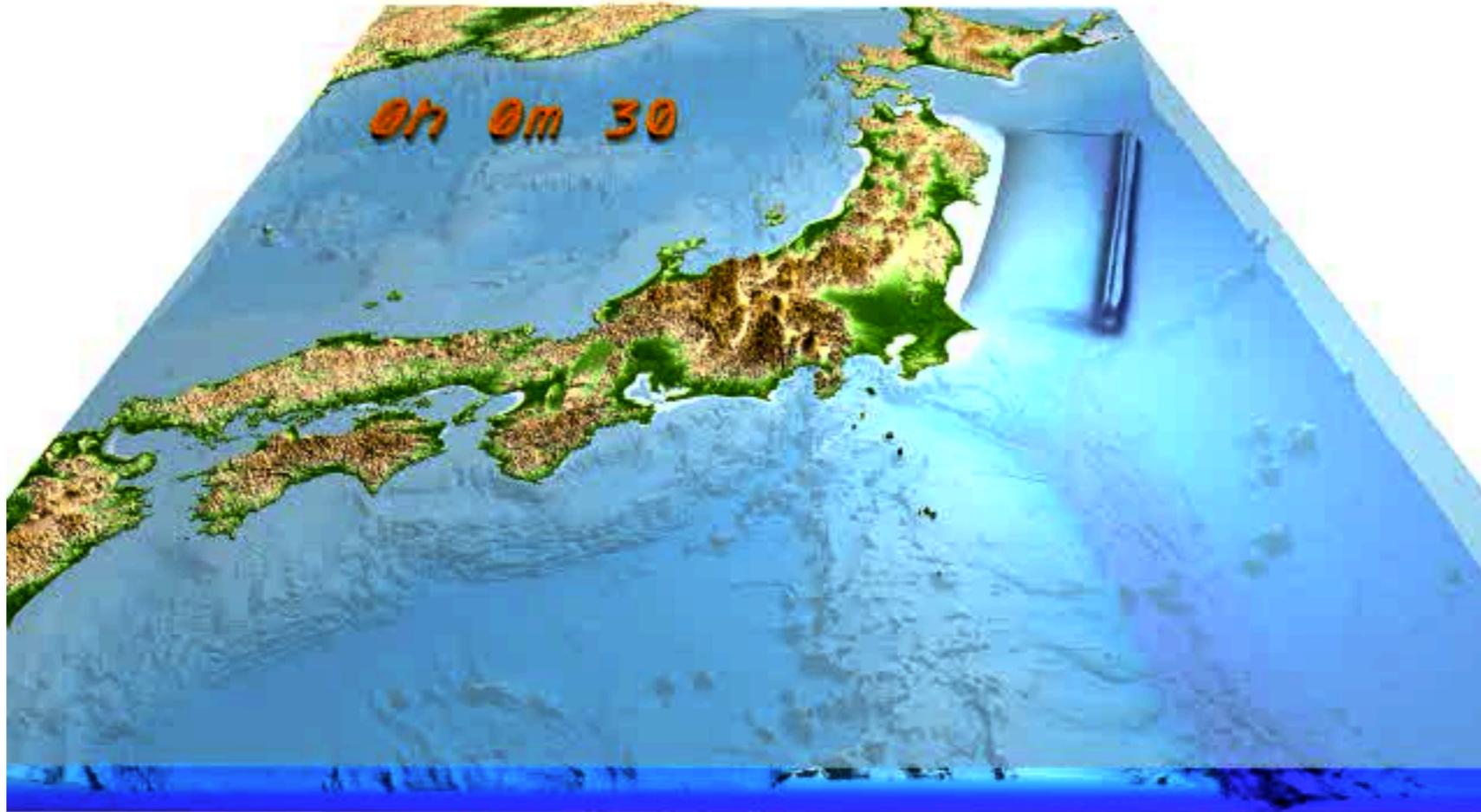
"Earthquake Research Institute, University of Tokyo, Prof. Takashi Furumura and Project Researcher Takuto Maeda"

Tsunami animation - NOAA
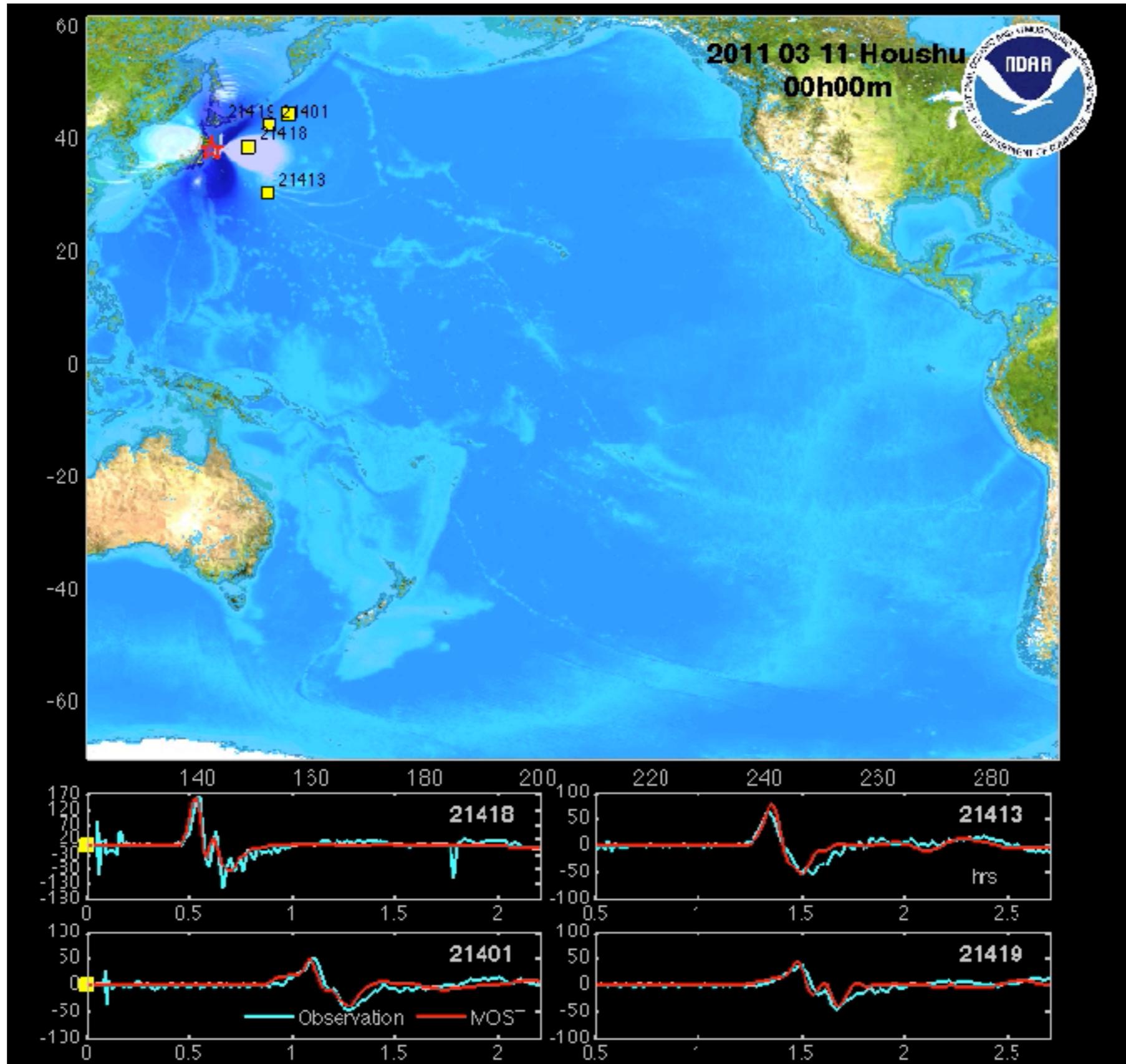
Tsunami signature in the ionosphere

By dynamic coupling with the atmosphere, acoustic-gravity waves are generated

Traveling Ionospheric Disturbances (TID) can be detected and monitored by high-density GPS networks
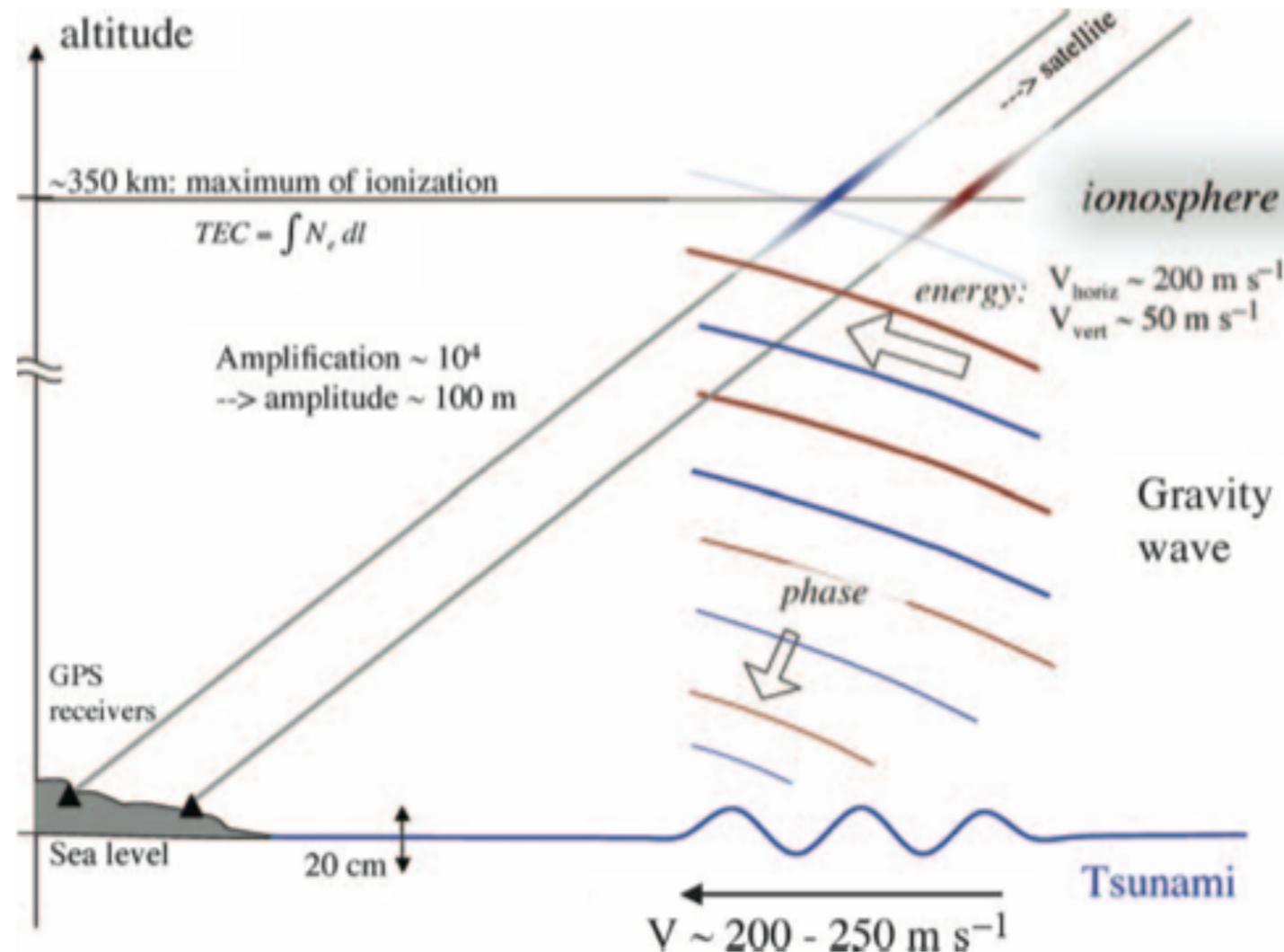
Tsunami signature in the ionosphere

Hines (1960): atmospheric Internal Gravity Waves

Peltier & Hines (1972): can generate ionospheric signatures in the plasma

Lognonné et al. (1998): Analytical Coupled model

Artru et al. (2005): ionospheric imaging can detect tusnami signatures. GPS JAPAN net was used to map Chilean Tsunami of 2001

Occhipinti et al. (2006): Sumatra tsunami mapped

Tsunami signature in the ionosphere

Tsunami-generated IGWs and the response of the ionosphere to neutral motion at 2:40 UT.
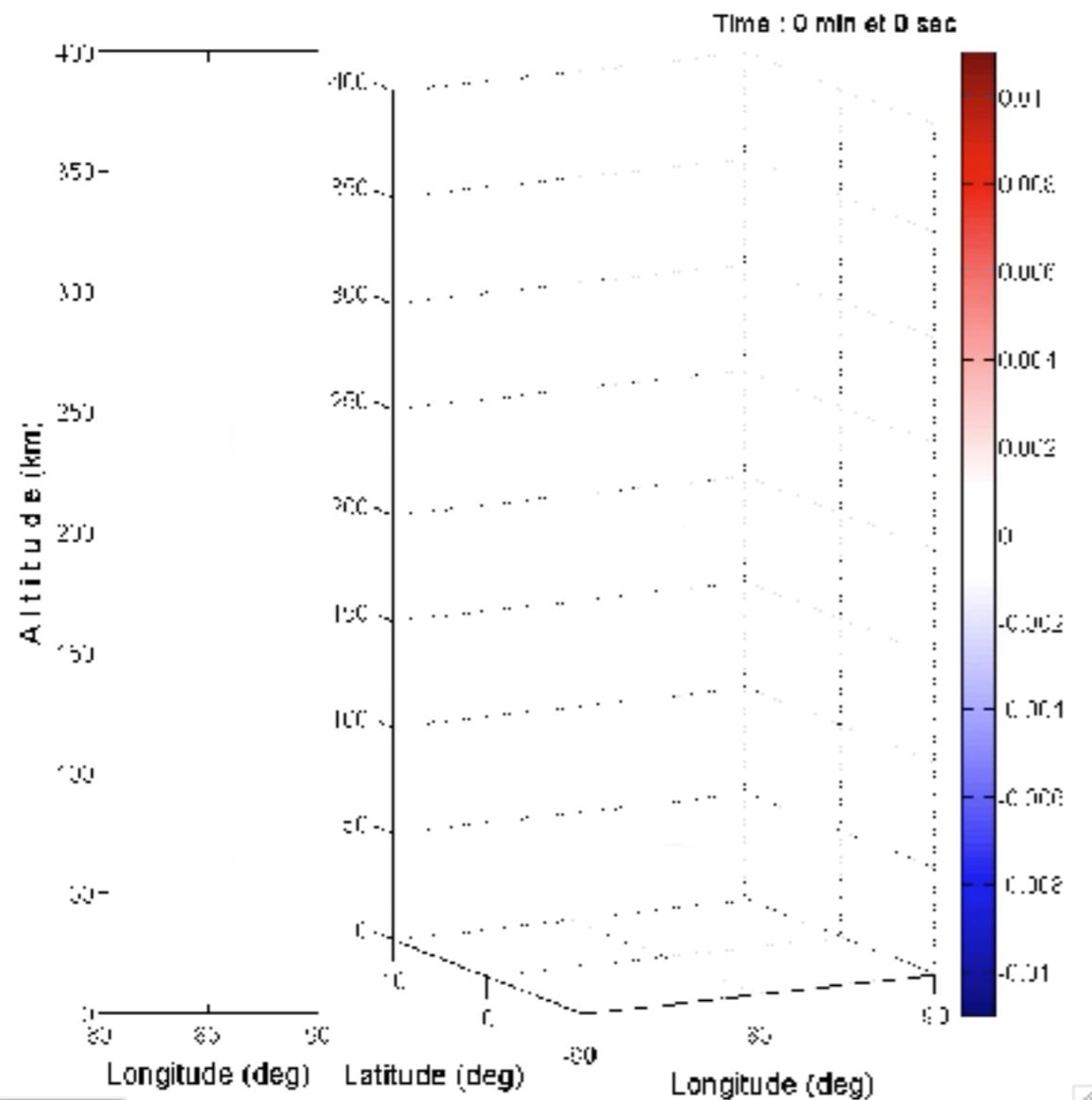
Normalized vertical velocity
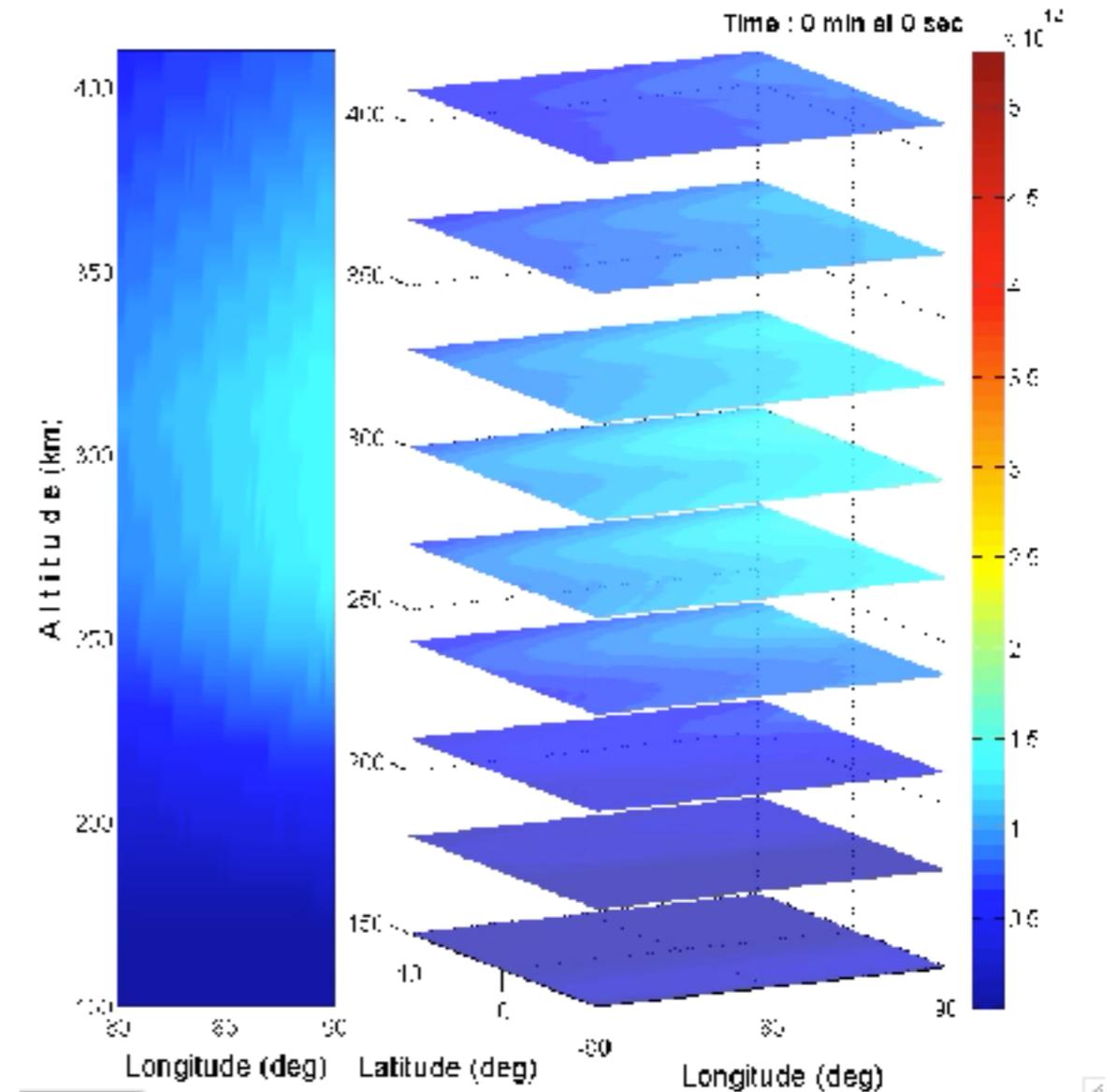
Perturbation in the ionospheric plasma

Tsunami signature in the ionosphere

Tohoku Tsunami Seen in Ionosphere Using GPS
Compared with JPL's Song Tsunami Model
UT Time: 11-Mar-2011 05:30:45

Observations from ~1200 GPS receivers
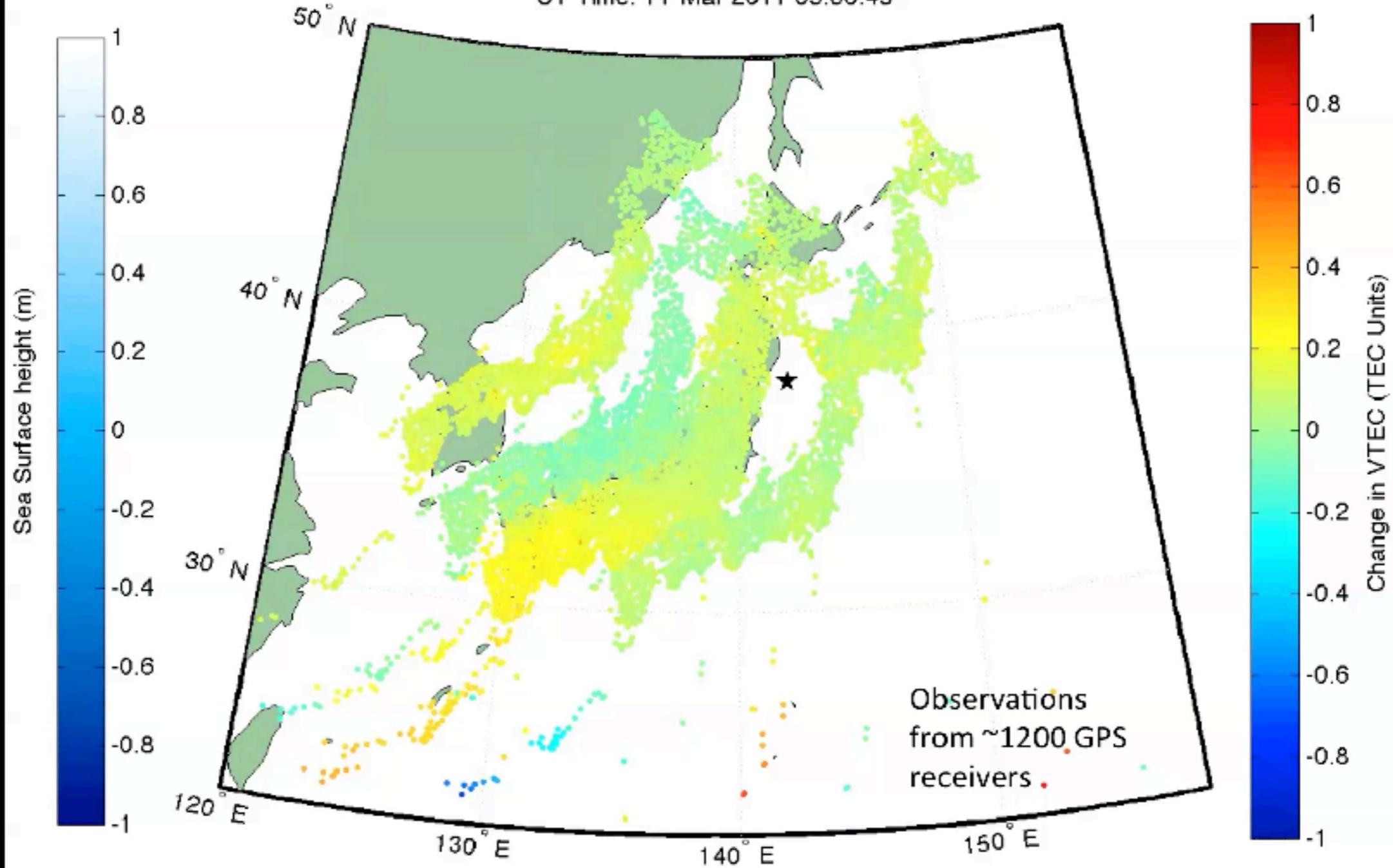
Risk, Hazard & Vulnerability

| Risk | = | Hazard | * | Vulnerability |

Nature decided, and can be assessed

Man decided, and can be reduced

$$R = \langle N_i, P_i, C_i \rangle$$

set of i-events with possible adverse consequences

associated probabilities of their occurrence

associated intolerable consequences

Expectations...
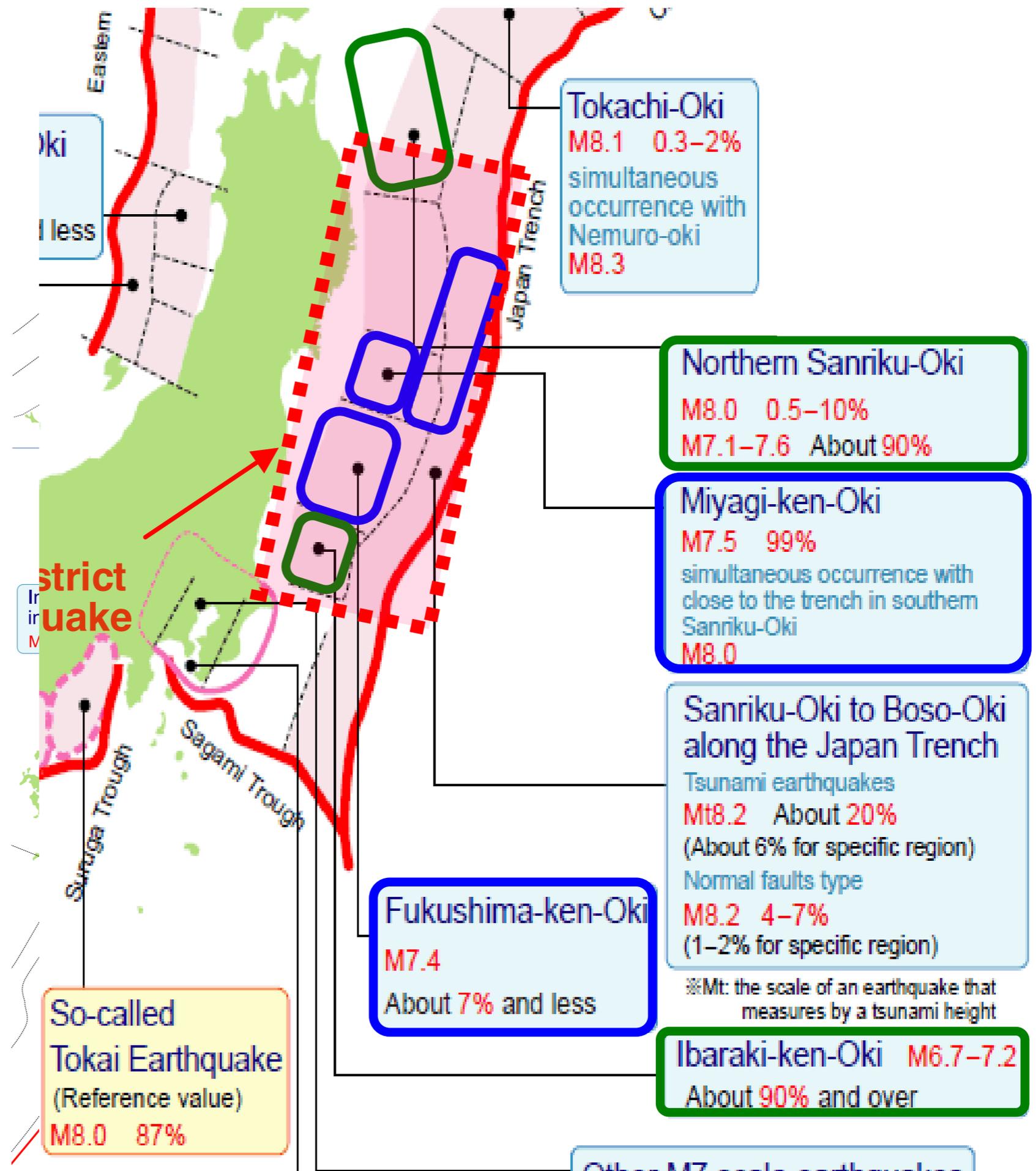
"Estimated magnitude and long-term possibilities within 30 years of earthquakes on regions of offshore based on Jan. 1, 2011."

"Estimated magnitude and long-term possibilities within 30 years of earthquakes on regions of offshore based on Jan. 1, 2008."

Tokachi-Oki
M8.1   0.3–2%
simultaneous occurrence with Nemuro-oki
M8.3

Northern Sanriku-Oki
M8.0   0.5–10%
M7.1–7.6   About 90%

Miyagi-ken-Oki
M7.5   99%
simultaneous occurrence with close to the trench in southern Sanriku-Oki
M8.0

Sanriku-Oki to Boso-Oki along the Japan Trench
Tsunami earthquakes
Mt8.2   About 20%
(About 6% for specific region)
Normal faults type
M8.2   4–7%
(1–2% for specific region)

※Mt: the scale of an earthquake that measures by a tsunami height

Fukushima-ken-Oki
M7.4
About 7% and less

Ibaraki-ken-Oki   M6.7–7.2
About 90% and over

So-called
Tokai Earthquake
(Reference value)
M8.0   87%

Reality...

Planning assumed maximum magnitude 8 Seawalls 5-10 m high

Magnitude 8
10 m tsunami

Magnitude 9
20 m tsunami

60 km
120 km
5m

200 km
500 km
10 m
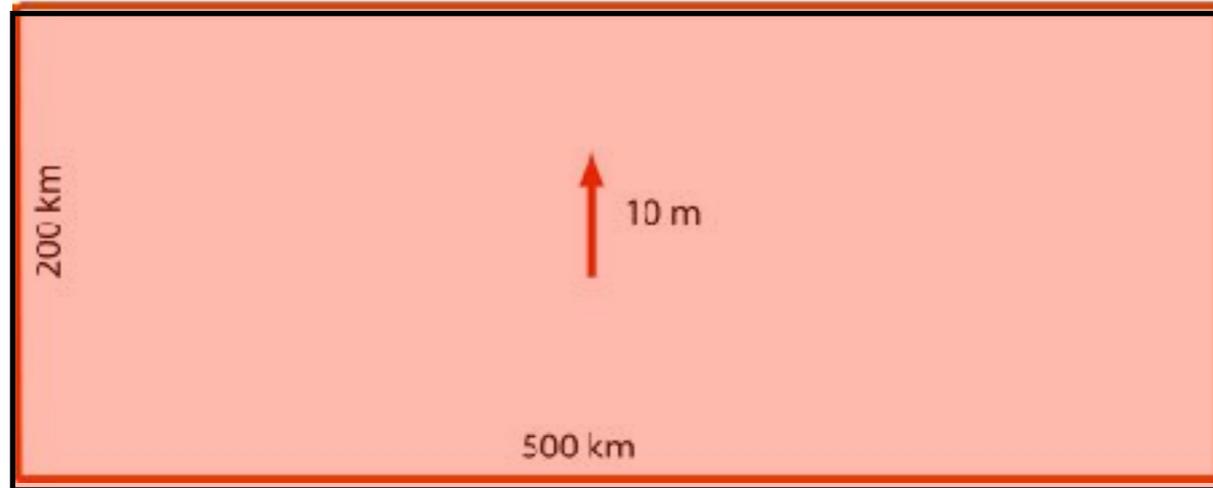
Tsunami runup approximately twice fault slip

M9 generates much larger tsunami

Stein, S. and E. Okal, The size of the 2011 Tohoku earthquake
needn't have been a surprise, EOS, 92, 227-228, 2011.

Table 1. Evolution of tsunami warning systems AFTER major tsunamis.

tsunami	resulting tsunami warning system
1896 Japan	Japan-1941
1946 Alaska, USA	USA-1949
1952 Kamchatka, Russia	Russia-1954
1960 Chile	International Pacific Basin-1965
1964 Alaska, USA	French Polynesia-1965
2004 Sumatra, Indonesia	Global- 2007

Tsunami Propagation Forecast

Contours of forecasted maximum wave amplitudes [cm], detailing tsunami energy propagation.

Event ID: lhvpd9
Earthquake Magnitude: 9.0
Earthquake Location: [38.322,142.369], "near the east coast of Honshu, Japan"

Origin Time: 05:46:26 (UTC)
Date: 3/11/2011

West Coast and Alaska Tsunami Warning Center
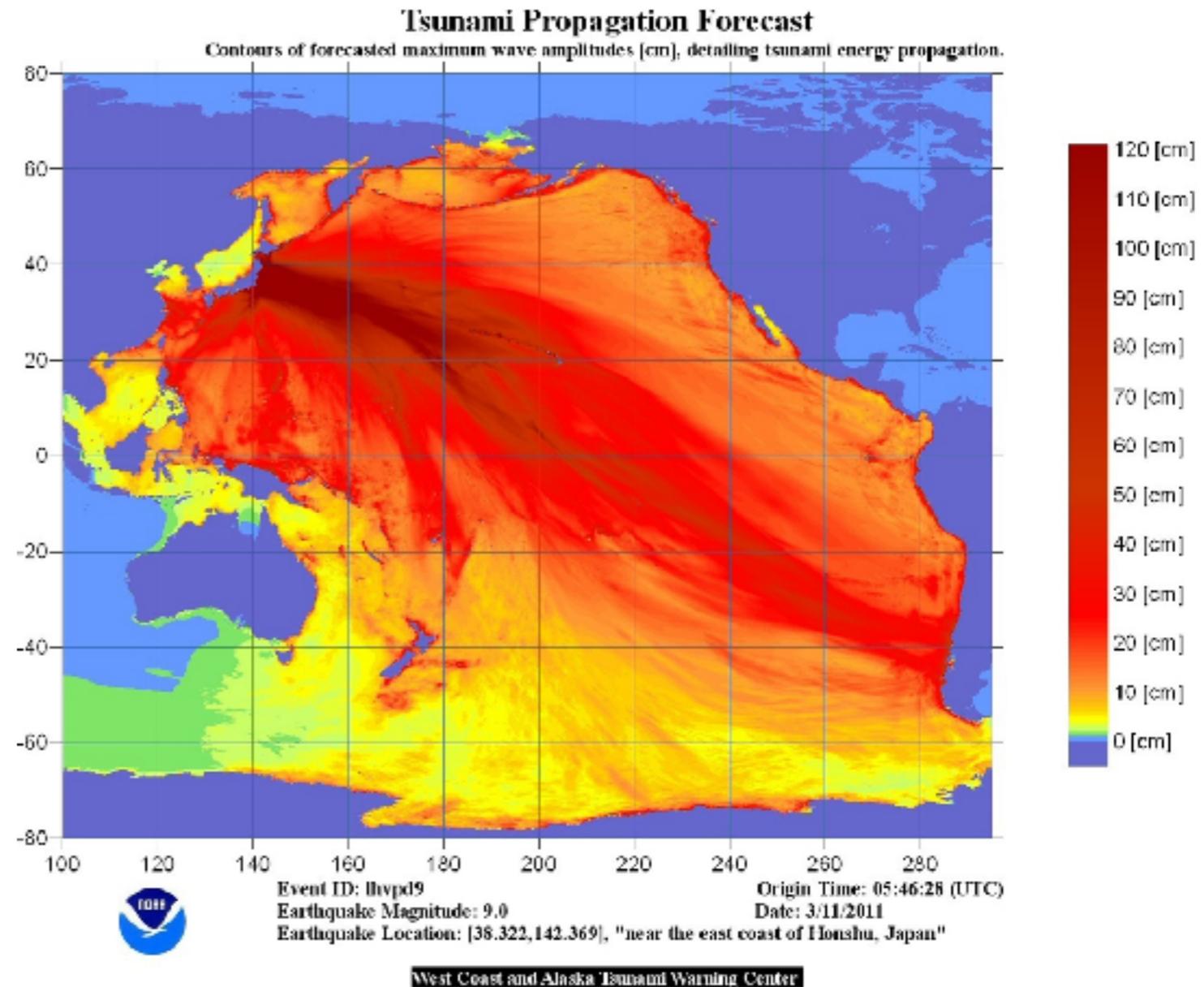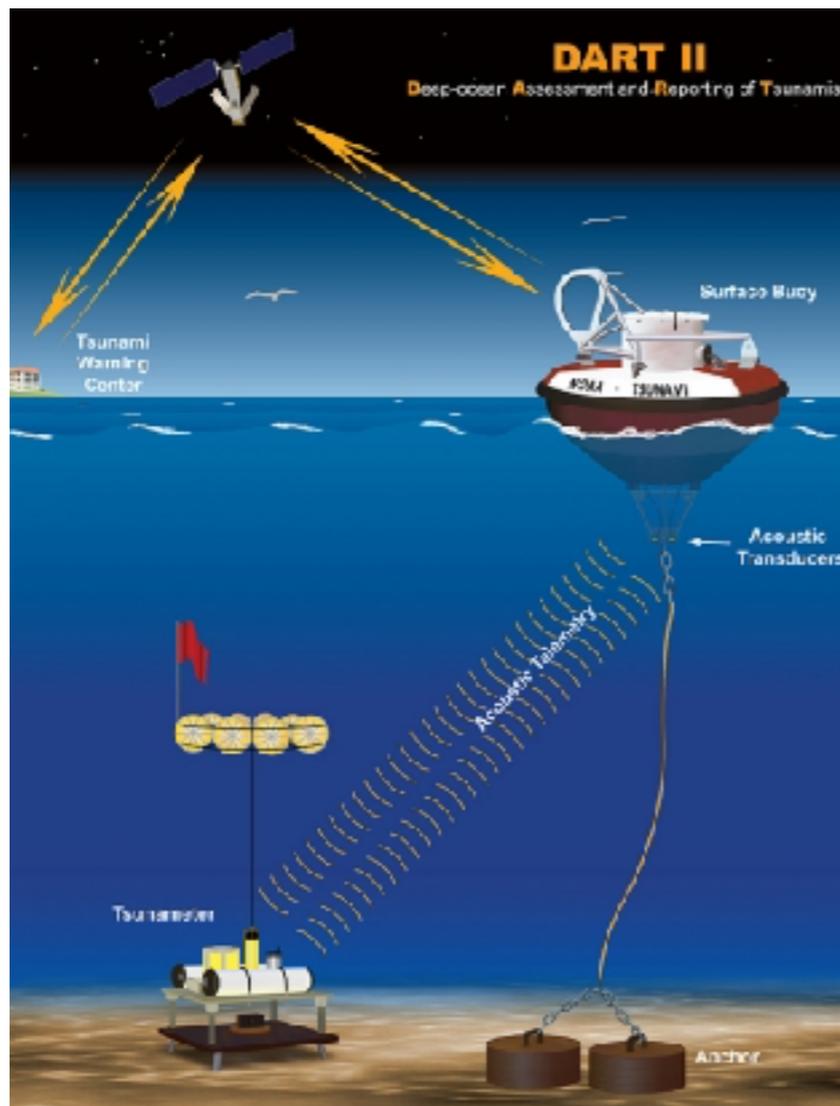
TEW - Japan

At night on 12 July 1993, an earthquake off the west coast of Hokkaido generated a huge tsunami. The southernmost area of Okushiri Island was completely devastated by the 11m tsunami, even though the area was protected by 4.5m seawalls.

In 1997, the Japan central government council, which consists of seven ministries, issued a guideline for comprehensive tsunami countermeasures that should be taken as part of regional tsunami disaster prevention.
In those guidelines, three basic concepts of tsunami countermeasures were recommended:

(i) building seawalls, breakwaters and flood gates to protect lives and properties;

(ii) urban planning to create a tsunami-resilient community through effective land-use management and arrangement of redundant facilities to increase the safe area, such as vertical evacuation buildings;

(iii) disaster information dissemination, evacuation planning and public education.

Koshimura S, Shuto N. 2015 Response to the 2011 Great East Japan Earthquake and Tsunami disaster. Phil. Trans. R. Soc. A 373: 20140373.

TEW - Japan

JMA prepared a pre-conducted tsunami propagation simulation database for over 100 000 earthquake scenarios around Japan.

The contents of the warning were classified into three categories, according to the estimation of tsunami height: 'Major tsunami' (estimated more than 3 m), 'Tsunami' (estimated 1 or 2 m) and 'Advisory' (0.5 m or less).

Sea gate in Hachinohe

http://minkara.carview.co.jp/userid/405365/car/375387/1923923/photo.aspx

Sea gate (9.3 m high)

http://ja2xt.mu-sashi.com/Numazu5.htm
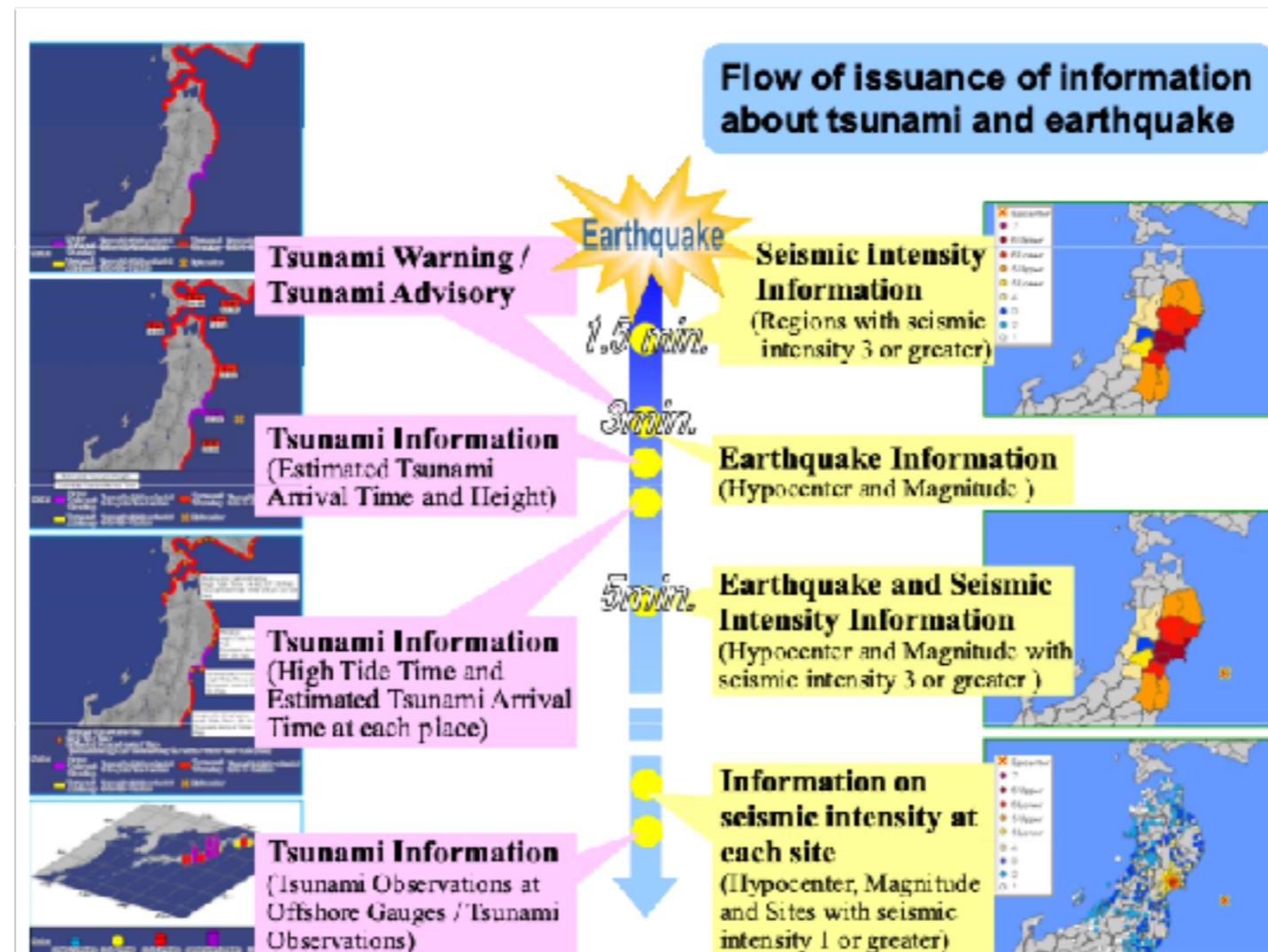
Sea walls

Sea wall with stairway evacuation route used to protect a coastal town against tsunami inundation in Japan.

Photo courtesy of River Bureau, Ministry of Land, Infrastructure and Transport, Japan.

Deepest breakwater in Kamaishi (Iwate)

Elevated platform used for tsunami evacuation that also serves as a high-elevation scenic vista point for tourist.
Okushiri Island, Japan. Photo courtesy of ITIC

Topping a 12 m sea wall

Tsunami walls...

The 2.4 km long tsunami wall in Miyako, Iwate Prefecture, was destroyed. The 6 m, 2 km long, wall in Kamaishi, Iwate Prefecture, was overwhelmed but delayed the tsunami inundation by 5 minutes.

The 15.5 m tsunami wall in Fundai, Iwate Prefecture, provided the best protection, but it is good to know that the original design was only 10 m. The village mayor fought to make it higher from information in the village historical records.

The biggest problem is that tsunami walls may give a false sense of security and other preparedness measures may NOT be undertaken.

Woody Epstein, 2011
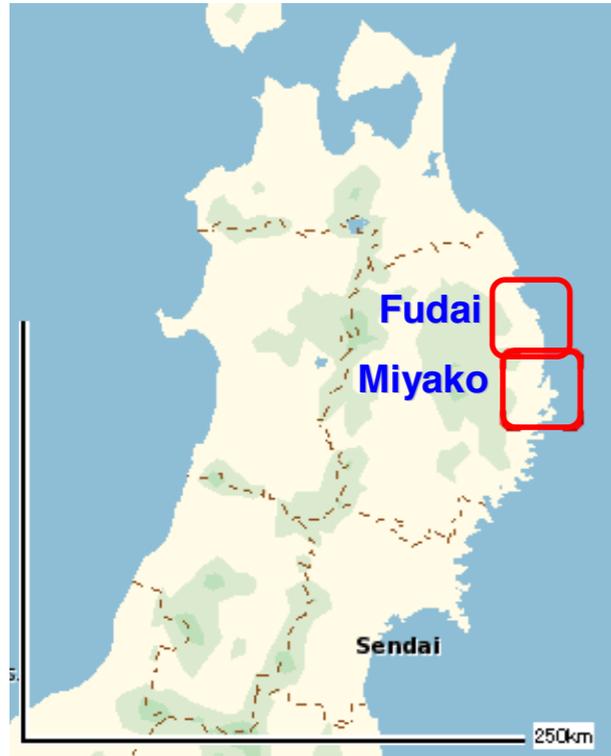
Sea wall at Fudai

49 foot sea wall:
completed in 1967; floodgates were added in 1984.

Following the 1896 Meiji tsunami, village mayor Kotoku Wamura pressed for a seawall at least 15 meters high, often repeating the tales handed down to him growing up: that the devastating tsunami was 15 meters.

Miyako and Fudai...

Miyako

Fudai

The 10m-high seawall was destroyed in Taro district, Miyako city, Iwate Pref.

The 15.5m-high seawall was undestroyed in Otabe district, Fudai village, Iwate Pref.

Fig. III-1-16 Difference of seawall heights resulting in different consequence.

The stone monument
Miyako

Miyako

A photo from the village's point of view (i.e. facing the coast)

A photo from a viewpoint of facing the village taken at the spot slightly below the stone monument

Fig. III-1-17 Photos of a stone monument and tsunami invading area below the stone monument.

Tsunami stones (Tsunami-seki)

TEW - Japan (Tohoku-oki March 11)

When the 2011 event occurred at 14.46 JST on 11 March, JMA's initial estimate of the magnitude was 7.9. Based on the promptly estimated magnitude 7.9, 3 min after the quake (14.49 JST), JMA issued a Major tsunami warning to the coasts of Iwate, Miyagi and Fukushima prefectures with estimates of 3 m, 6 m and 3 m, respectively.

After the tsunami was observed at offshore tsunami buoys, JMA revised the contents of the warning with estimates of 3 m, 6 m, over 10 m, 6 m, 4 m and 4 m to the coasts of Aomori, Iwate, Miyagi, Fukushima, Ibaraki and Chiba prefectures.

Receiving the tsunami warning from JMA, some residents claimed that they thought they were safe based on the 3 m estimation: they did not feel that they had to evacuate, as they felt safe behind a 10 m seawall. Even worse, in several communities, the radio or speaker system did not work because of the blackout caused by the earthquake.
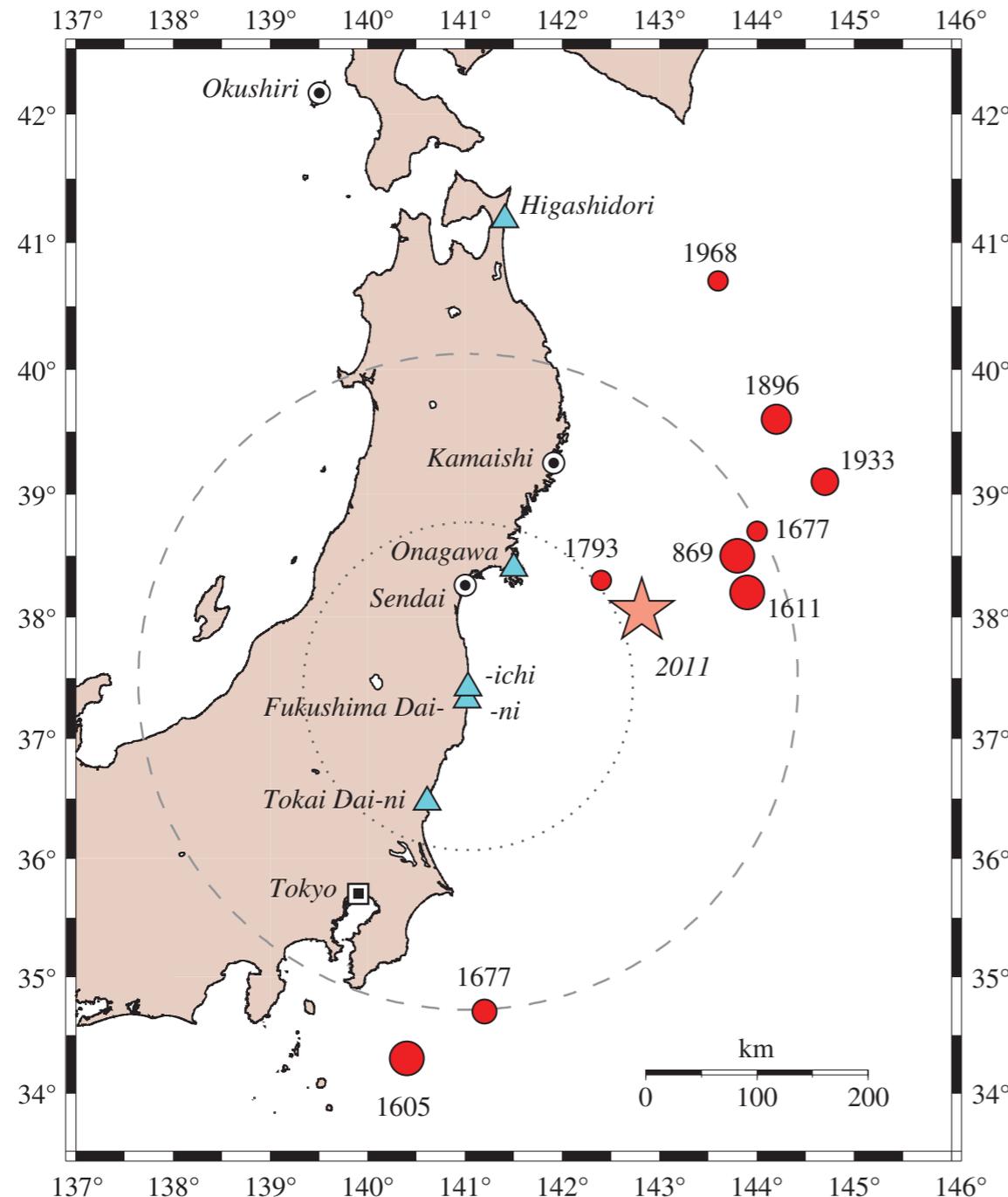
A tale of two NPPs

Figure 1. Locations of NPPs (triangles) affected by the 11 March 2011 earthquake (star) and tsunami, and relevant historical earthquakes in North East Japan listed in the 1974 catalogue of Soloviev & Go [14]. Events are shown with red dots, whose radius is adjusted to the Soloviev tsunami intensity scale; 150 and 300 km radius circles from Fukushima Dai-ichi are shown with dotted and dashed lines, respectively, depicting the region over which international standards require consideration of hazard sources.

Table 2. Summary of NPPs design conditions and damage to power supplies.

NPPs	pre-2011 estimated tsunami heights (m) [16,32]	2011 tsunami heights/ NPP elevations (m) [32]	off-site power lines damaged/total [33]	EDGs damaged/ total [33]
Onagawa[a]	13.6[c]	13/14.8[f]	4/5	2/8
Fukushima Dai-ichi[a]	6.1[d]	13/10-13	6/6	12/13
Fukushima Dai-ni[a]	5.0[e]	9/12	3/4	9/12
Tokai Dai-ni[b]	5.7[e]	5/8	3/3	1/3

[a]Elevations are relative to Onahama Peil (O.P.), which is 0.74 m below standard mean sea level of Tokyo Bay. This reference water level was used for Onagawa and Fukushima NPPs.
[b]Mean sea level at Hitachi Point (H.P.) was used as reference level at Tokai Dai-ni.
[c]Determined based on Sanriku earthquakes.
[d]Determined based on Shioyazaki-oki earthquake [34].
[e]Determined based on the tsunami source model set by Ibaraki Prefecture.
[f]This was the original plant height. There was 1 m subsidence at the site due to earthquake.

https://royalsocietypublishing.org/doi/10.1098/rsta.2014.0379

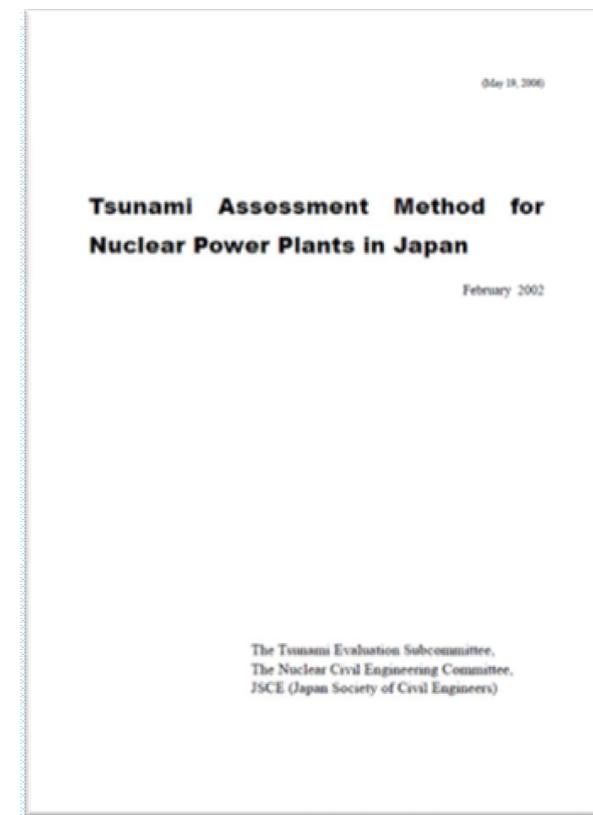# Tsunam Assessment method for NPP in JSCE, Japan

The TSUNAMI EVALUATION SUBCOMMITTEE,
Nuclear Civil Engineering Committee, JSCE

Masafumi Matsuyama (CRIEPI)

History of TES

- **Phase I 1999-2000**
  The maximum and minimum water levels by deterministic method
    → `Tsunami assessment method for NPP in Japan」 2002)"

- **Phase II 2003-2005**
  Probabilistic Tsunami Hazard Analysis for the max. and min. water levels
  Numerical simulation of nonlinear dispersion wave theory with soliton fission
     and split wave-breaking
  Tsunami wave force on breakwater

- **Phase III 2006-2008**
  Topography change due to tsunami
  Development of probabilistic Tsunami Hazard Analysis

- **Phase IV 2009-2011**
  Now
  Revising of Tsunami assessment method for NPP in Japan

(May 19, 2006)

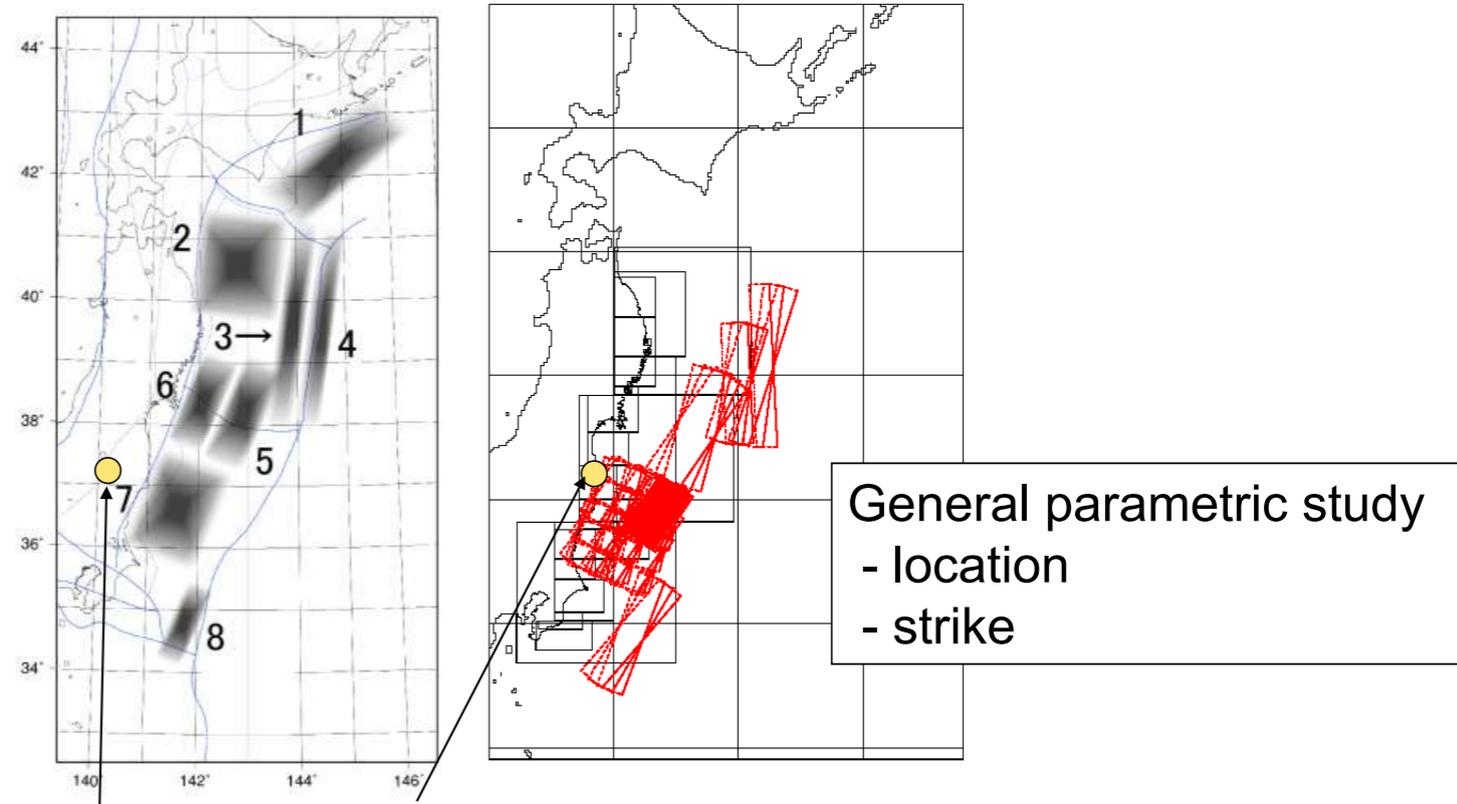**Tsunami Assessment Method for Nuclear Power Plants in Japan**

February 2002

The Tsunami Evaluation Subcommittee,
The Nuclear Civil Engineering Committee,
JSCE (Japan Society of Civil Engineers)

Tsunami Assessment method for NPP in JSCE, Japan

The TSUNAMI EVALUATION SUBCOMMITTEE,
Nuclear Civil Engineering Committee, JSCE

Masafumi Matsuyama (CRIEPI)
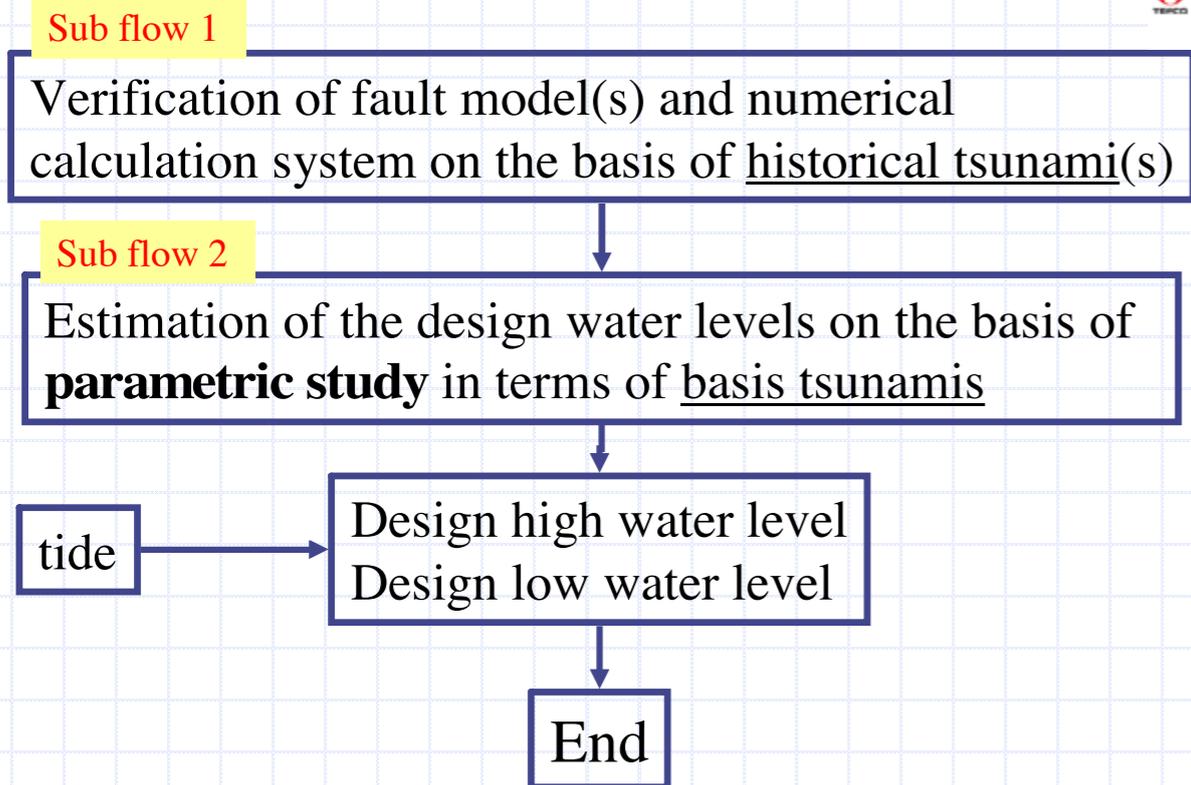
Deterministic method (2002)
Main flow chart

Sub flow 1

Verification of fault model(s) and numerical calculation system on the basis of historical tsunami(s)

Sub flow 2

Estimation of the design water levels on the basis of **parametric study** in terms of basis tsunamis

tide

Design high water level
Design low water level

End

General parametric study in the near field

Fukushima Daiichi NPS

General parametric study
- location
- strike

東京電力

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Summary of Evaluation

Maximum water level = 4.4m + O.P.＋1.3m ＝ O.P.+5.7m
Minimum water level = -3.6m － O.P.±0.0m ＝ O.P.-3.6m

O.P.+10～13m S/B T/B R/B

Maximum water level
O.P.+5.7m

Mean tide level
O.P.+0.8m

O.P.-3.6m
Minimum water level

Fukushima Daiichi NPS
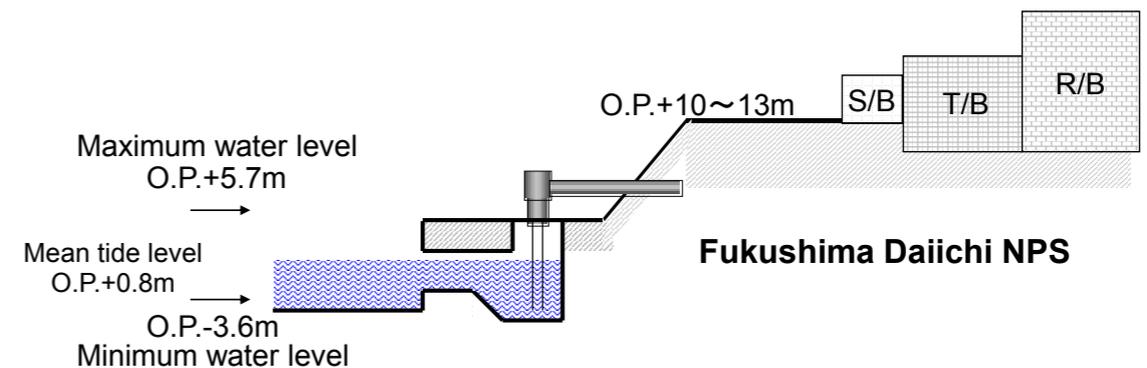
We assessed and confirmed the safety of the nuclear plants based on the JSCE method which was published in 2002.
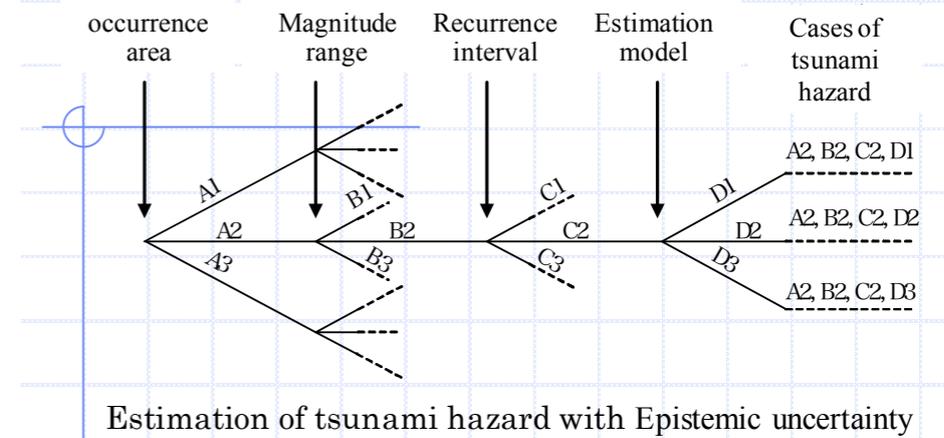
Niigata meeting, November 2010
http://www.jnes.go.jp/seismic-symposium10/presentationdata/3_sessionB.html

Tsunami Assessment method for NPP in JSCE, Japan

The TSUNAMI EVALUATION SUBCOMMITTEE,
Nuclear Civil Engineering Committee, JSCE
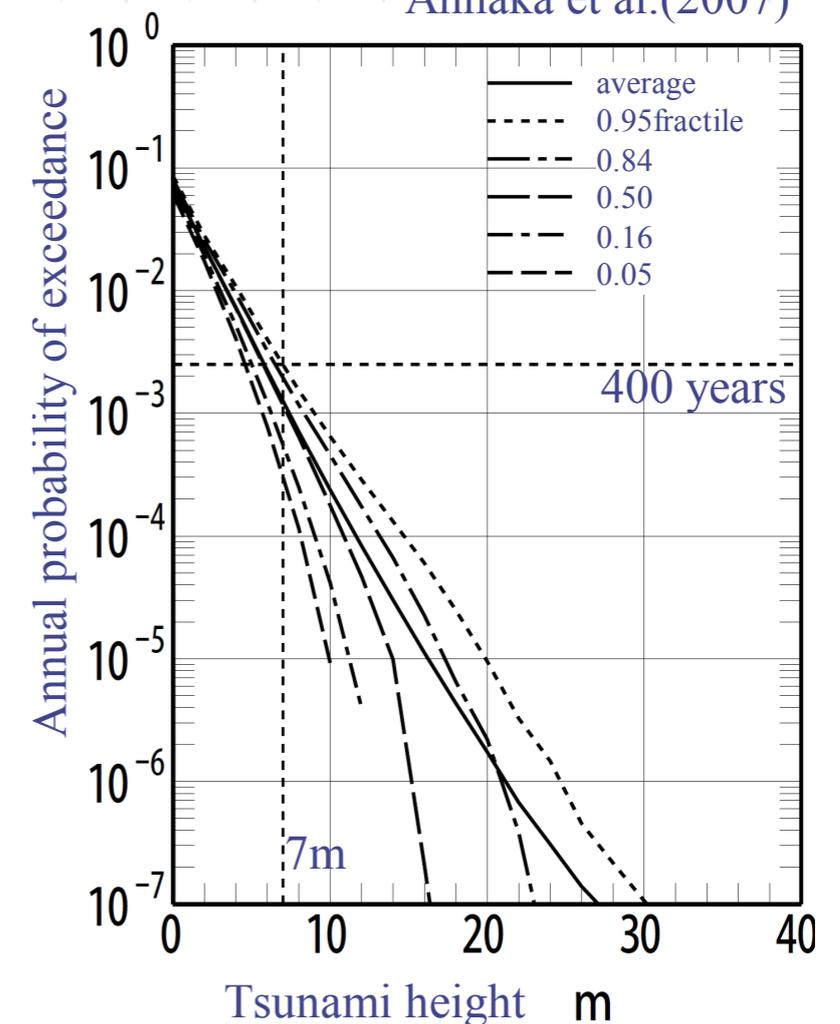
Masafumi Matsuyama (CRIEPI)

Logic-tree
Annaka et al.(2007)

Estimation of tsunami hazard with Epistemic uncertainty

Probabilistic Tsunami Hazard Analysis (PTHA)

- ◆ Probabilistic estimation of tsunami risk
  - Estimation of the <u>deterministic design tsunami</u>

- ◆ Considering uncertainties in estimation
  - Errors in fault parameters
  - Errors in the numerical calculation system (numerical simulation, topography data)
  - Incomplete knowledge and data about the earthquake process

Fractile hazard curve
Annaka et al.(2007)

Tsunami Assessment method for NPP in JSCE, Japan

The TSUNAMI EVALUATION SUBCOMMITTEE,
Nuclear Civil Engineering Committee, JSCE

Masafumi Matsuyama (CRIEPI)

## A brief review of recent activities
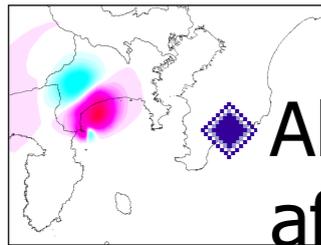
♦ Almost ten years have passed after tsunami manual released.
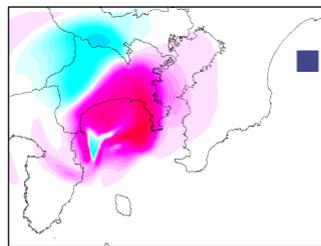
- Recent advances and new knowledge
  - ♦ Tsunami source model (fault model)
    - Re-evaluation of historical tsunami faults
    - Spatial inhomogeneity in terms of slip
  - ♦ Numerical simulation
    - New simulation method of crustal motion (GMS, Grand Motion Simulator by NIED*)
    - New simulation method of far field tsunami
      - Nonlinear dispersion theory
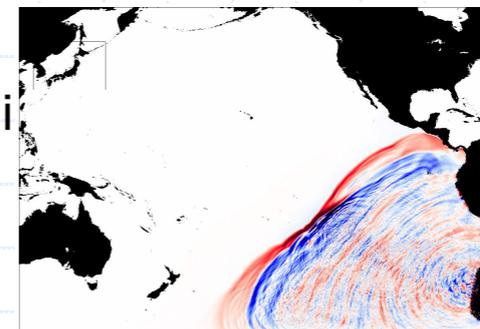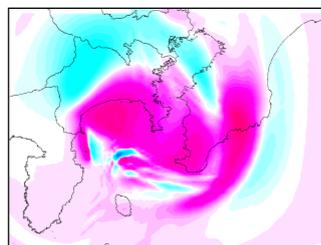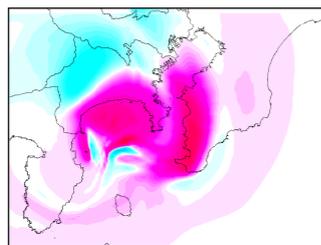
*National Research Institute for Earth Science and Disaster Prevention, Japan

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