The Abdus Salam International Centre for Theoretical Physics

ICTP Diploma Programme

Earth System Physics

Seismology

Tsunami physics & hazard

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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

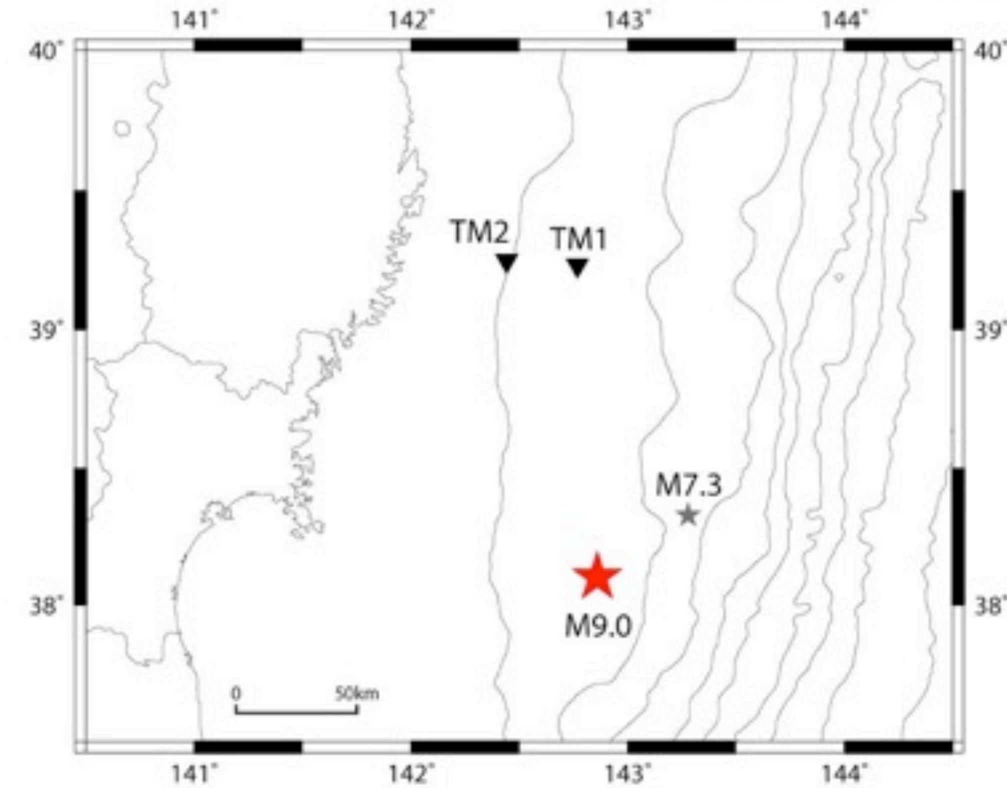


図1　釜石沖ケーブル式海底水圧計の位置

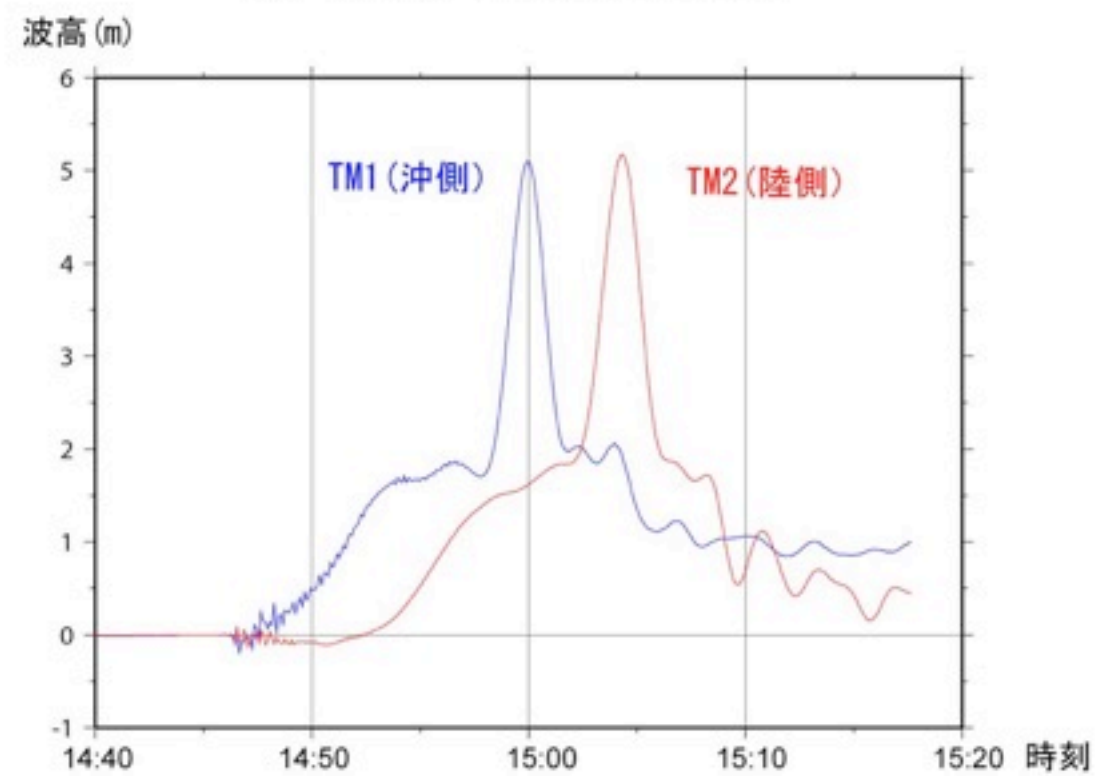
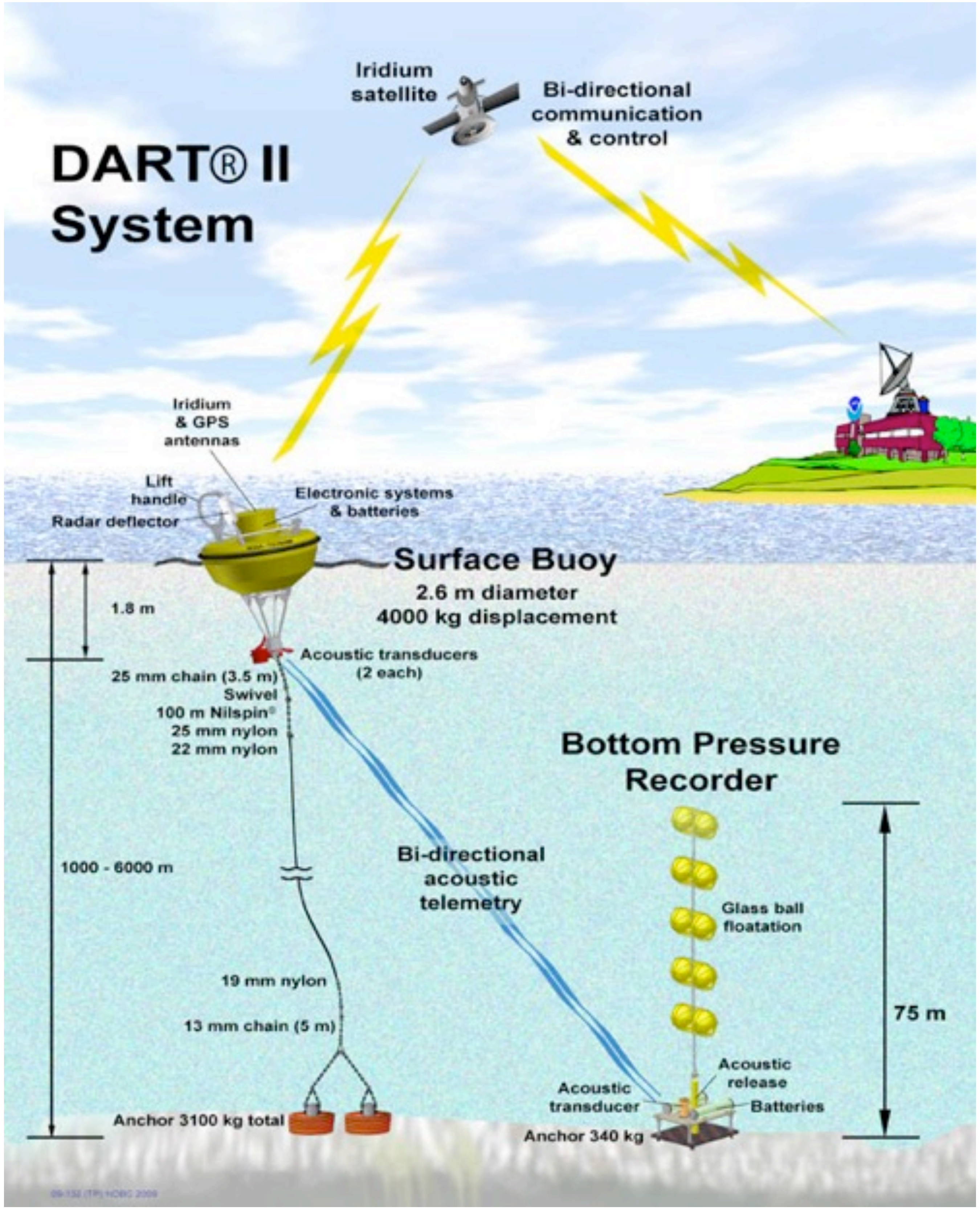


図2　海底水圧計の観測記録。14時46分頃、本震(M9.0)の振動が水圧計に伝わり、TM1(海寄り)では、その時から徐々に海面が上昇している。約2m上昇し、約11分後にはさらに約3m急激に上昇し、合計約5m海面が上昇した。約30km陸寄りに設置されているTM2では、TM1から約4分遅れて同様の海面上昇を記録した。

Dart buoys



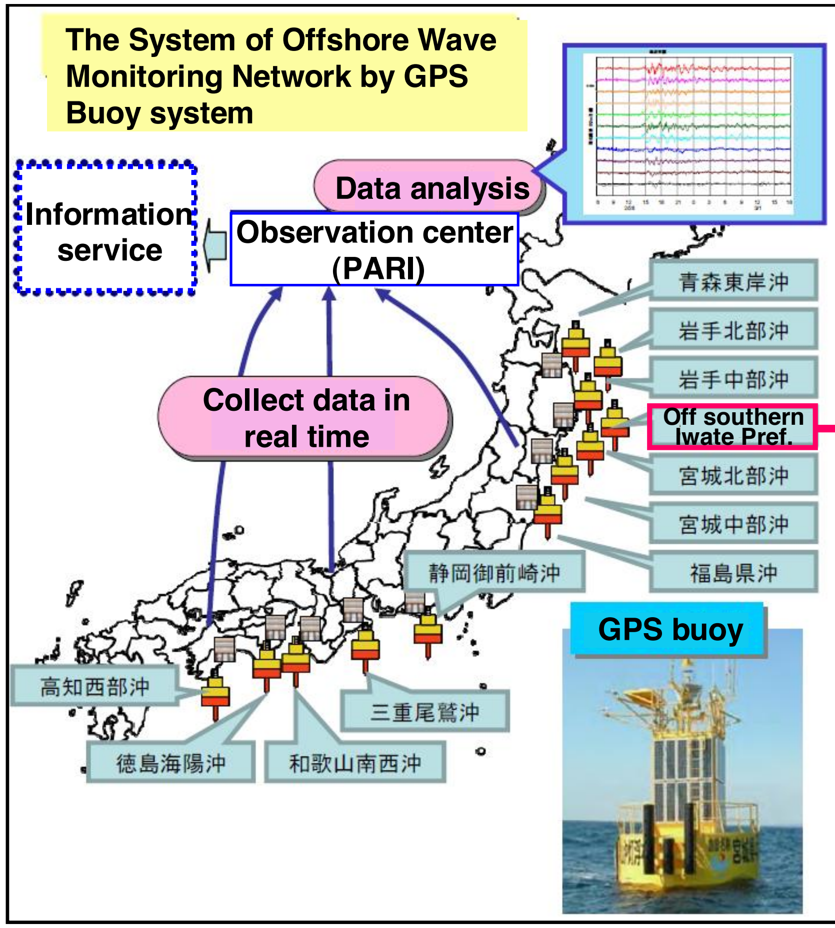
The DART II® system consists of a seafloor bottom pressure recording (BPR) system capable of detecting tsunamis as small as 1 cm, and a moored surface buoy for real-time communications.

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.

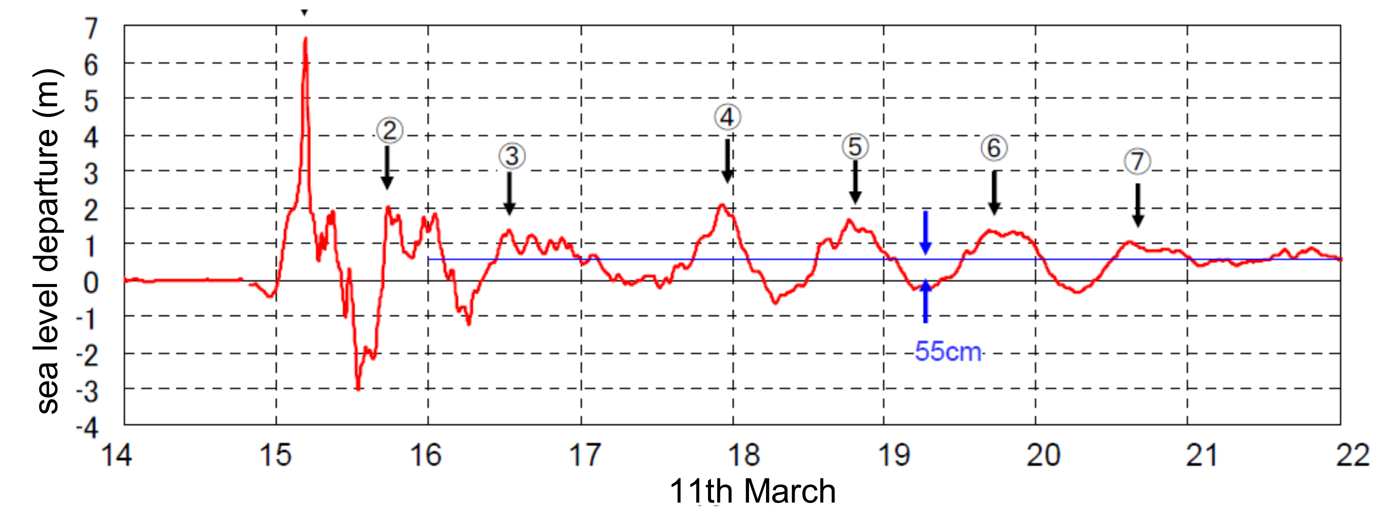
DART II systems transmit standard mode data, containing twenty-four estimated sea-level height observations at 15-minute intervals, once very six hours.

NOAA

Tsunami wave characteristics

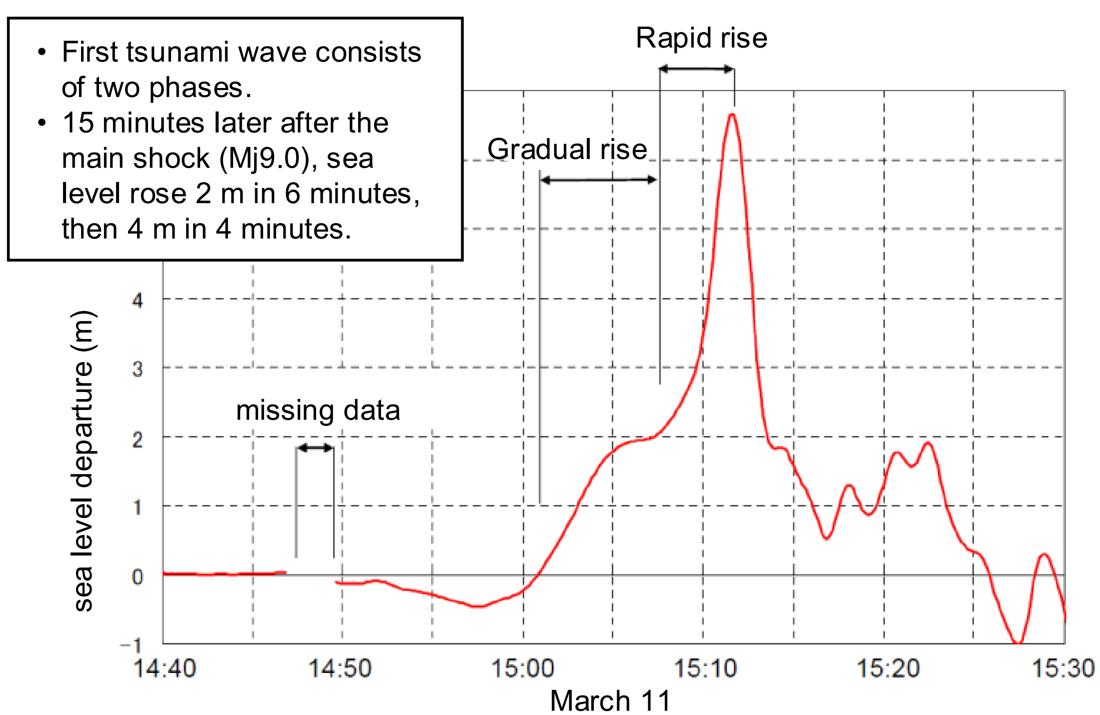


Tsunami waveform record from GPS buoy data off southern Iwate Pref. (204m off Kamaishi)

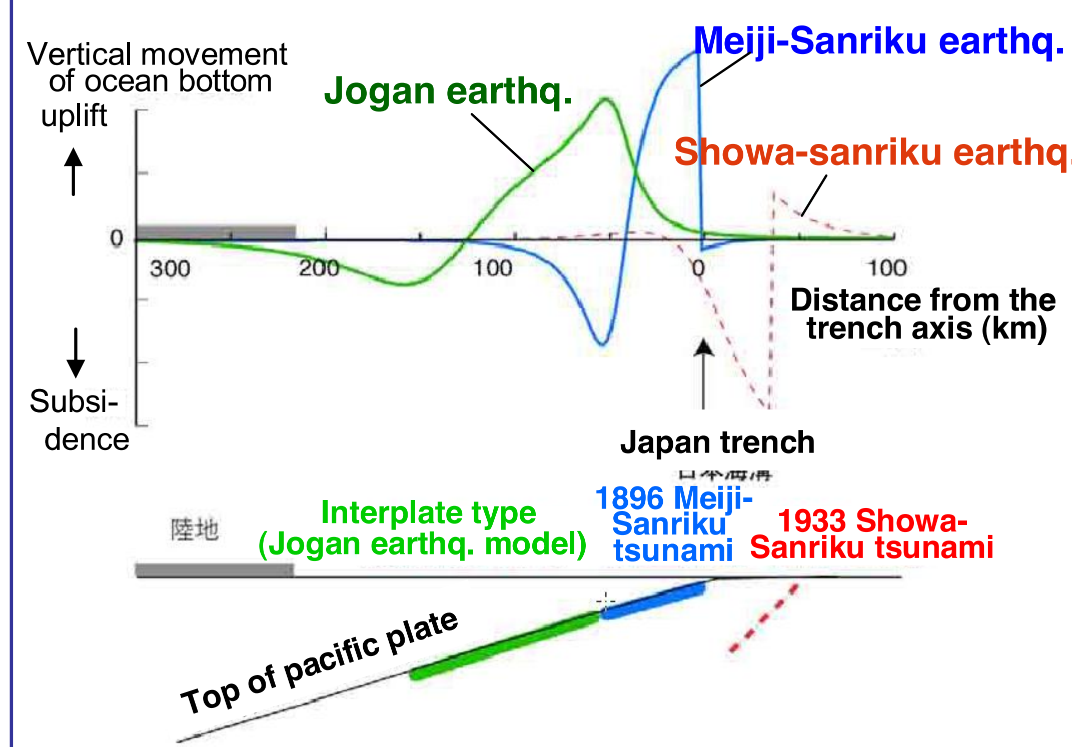


- The maximum wave height was 6.7 m (first wave) off southern Iwate Pref. at 15:12.
- First tsunami wave was extremely high.
- Wave period
  - First to third tsunami wave: irregular period
  - Fourth to seventh tsunami wave: about 50 minutes period
- Total amount of rose in average sea level were 55 cm after the earthquake.

Reference: Independent Administrative Institute Port and Airport Research Institute

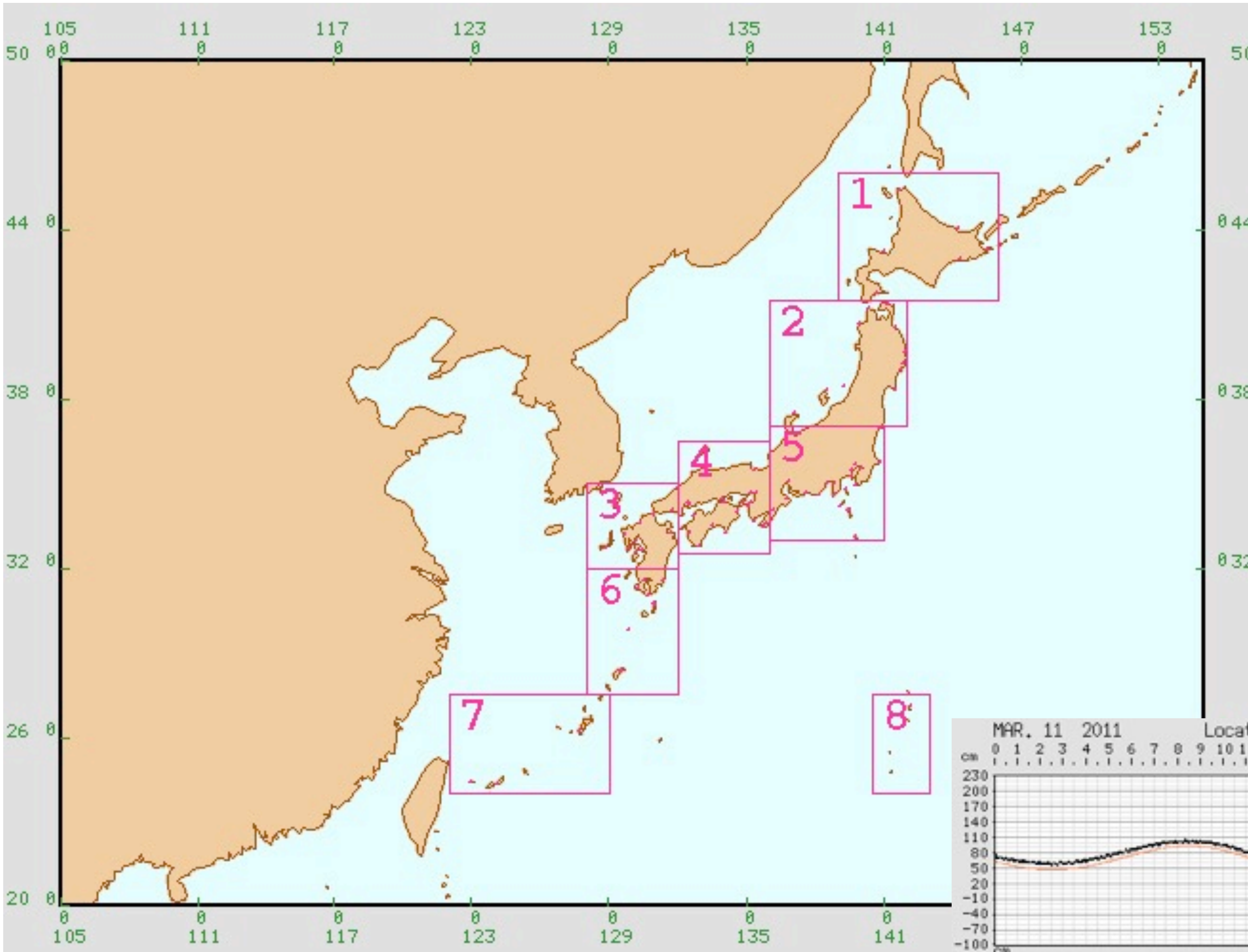


Reference: Independent Administrative Institute Port and Airport Research Institute



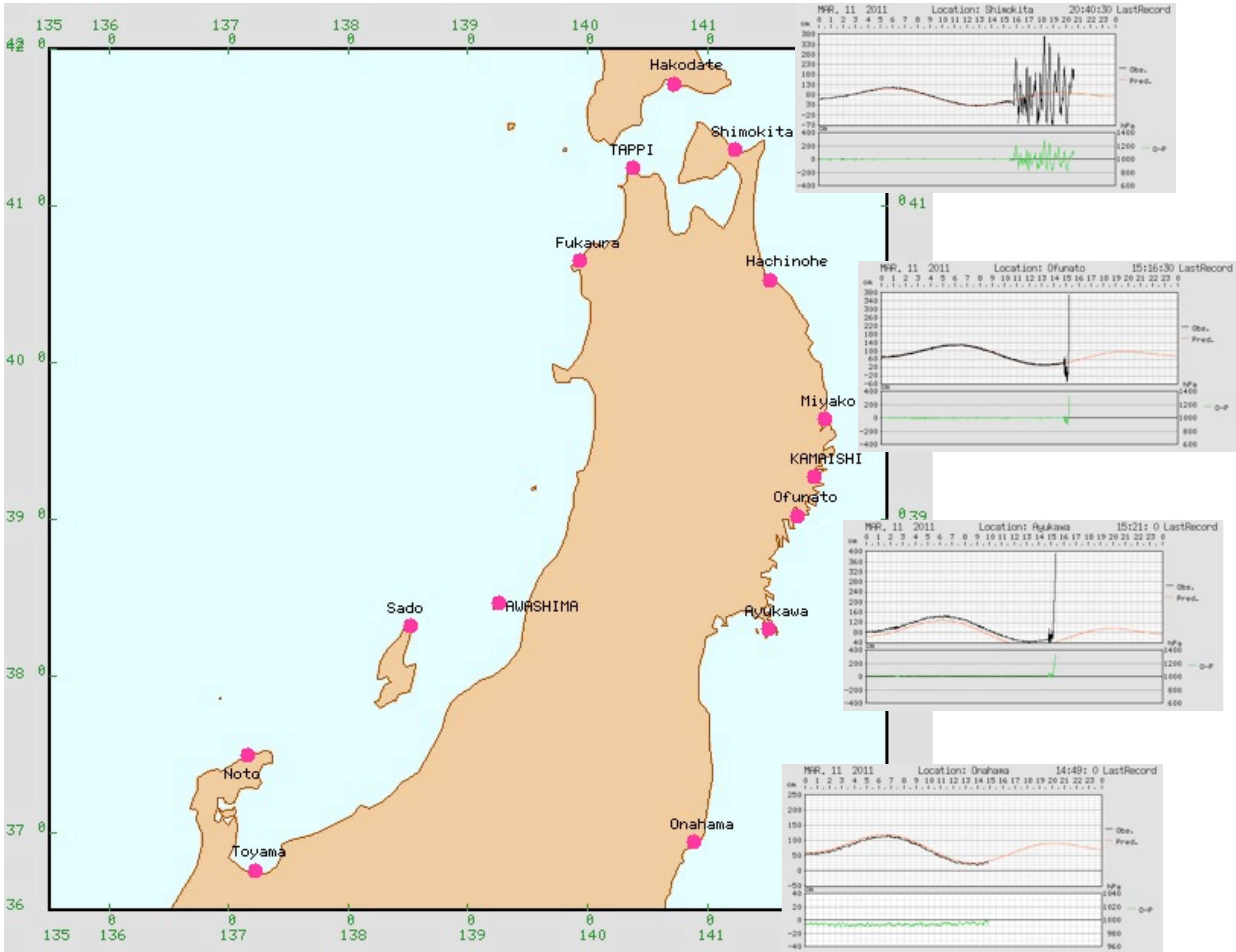
Reference : Satake (2011) Paper preparing for NIED meeting on Apr.17.

Tsunami data



http://www1.kaiho.mlit.go.jp/KANKYO/TIDE/real_time_tide/sel/index_e.htm

Tsunami data



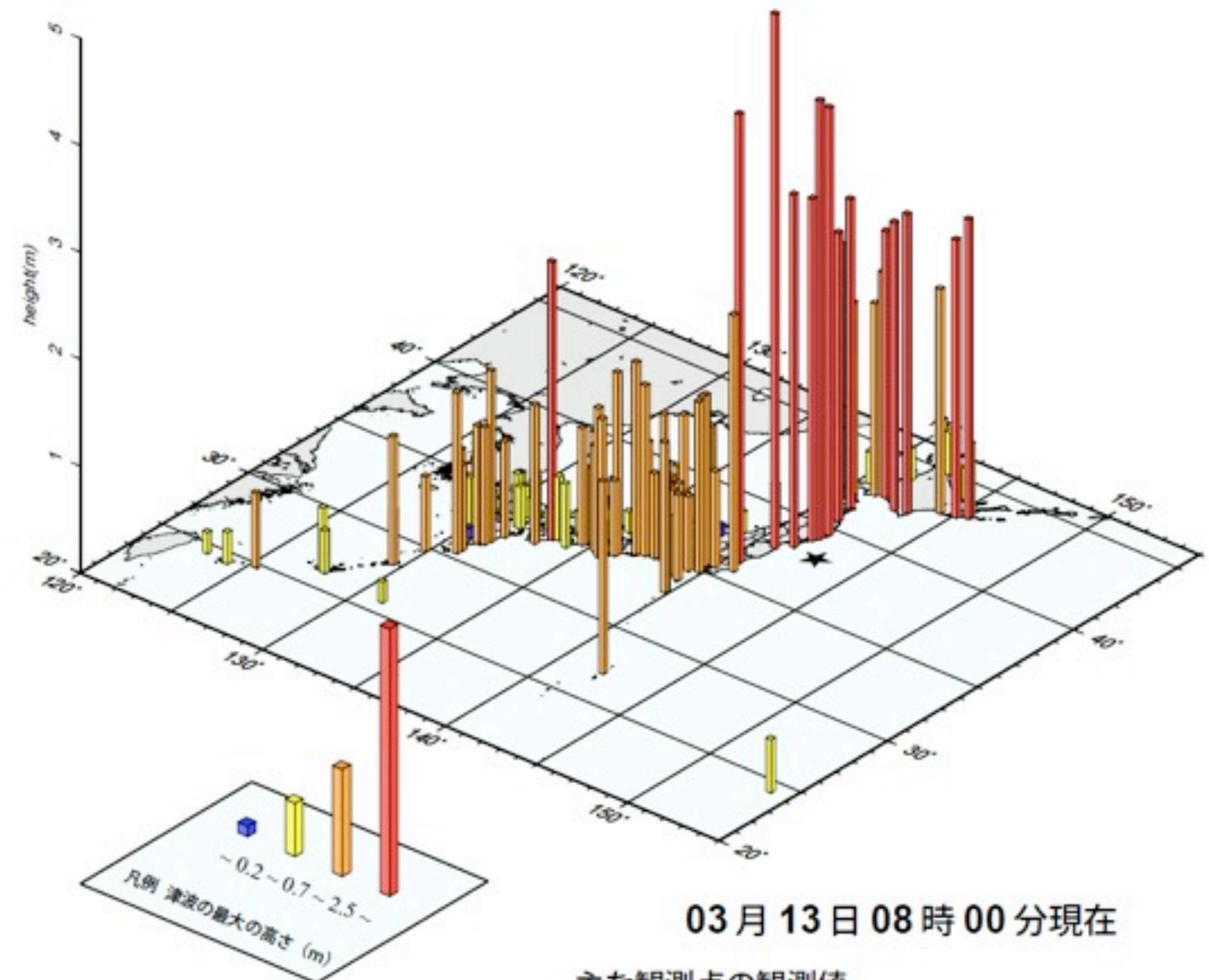
http://www1.kaiho.mlit.go.jp/KANKYO/TIDE/real_time_tide/sel/index_e.htm

Distribution of tsunami heights

Figure from the
Headquarters for
Earthquake Research
Promotion
(at March 13)

http://www.jishin.go.jp/main/index-e.html

津波観測状況

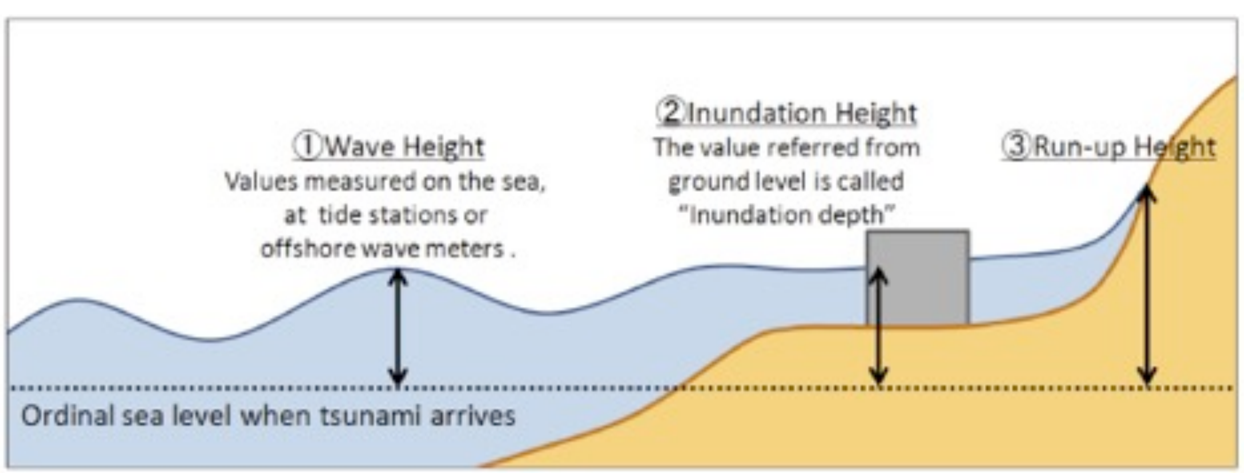


03月13日08時00分現在

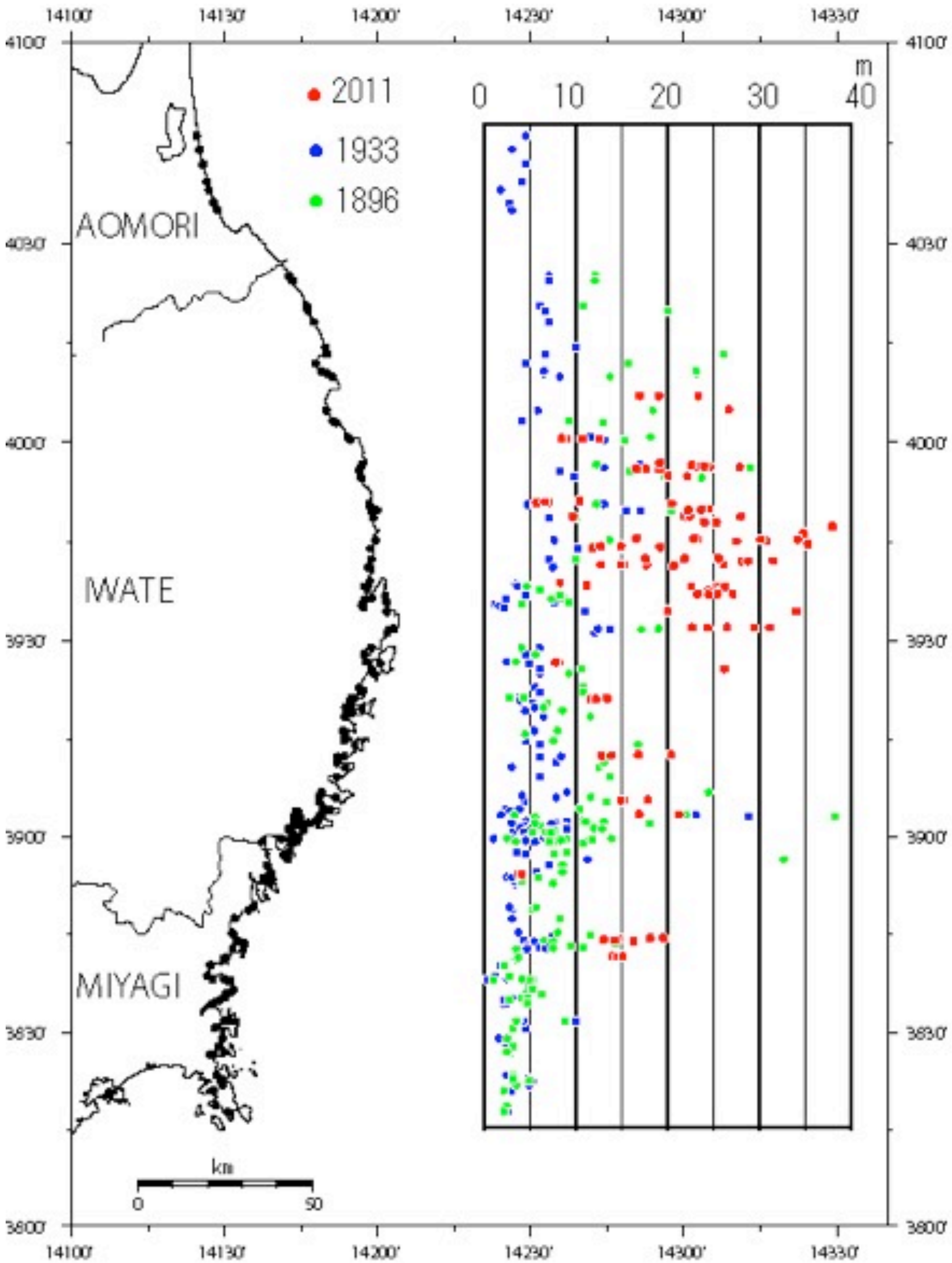
主な観測点の観測値

	第一波			最大波	
相馬	11日 14時 55分	押し	0.3m	11日 15時 50分	7.3m以上
大洗	11日 15時 15分	押し	1.8m	11日 16時 52分	4.2m
釜石	11日 14時 45分	引き	0.1m	11日 15時 21分	4.1m以上
宮古	11日 14時 48分	押し	0.2m	11日 15時 21分	4.0m以上
石巻市鮎川	11日 14時 46分	押し	0.1m	11日 15時 20分	3.3m以上
大船渡	11日 14時 46分	引き	0.2m	11日 15時 15分	3.2m以上
むつ市関根浜	11日 15時 20分	引き	0.1m	11日 18時 16分	2.9m
根室市花咲	11日 15時 34分	引き	微弱	11日 15時 57分	2.8m
十勝港	11日 15時 26分	引き	0.2m	11日 15時 57分	2.8m以上
浦河	11日 15時 19分	引き	0.2m	11日 16時 42分	2.7m

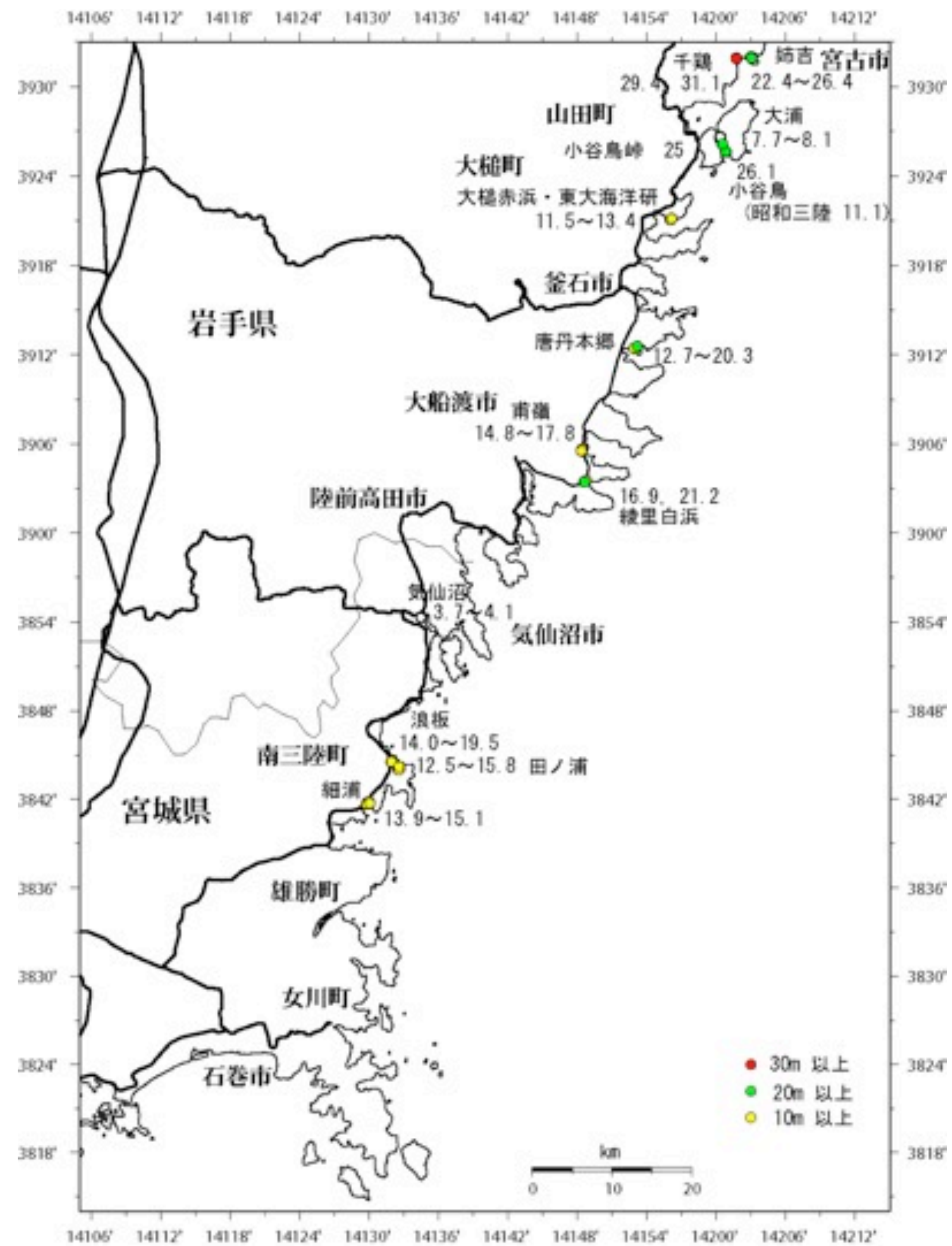
気象庁作成



Distribution of tsunami heights



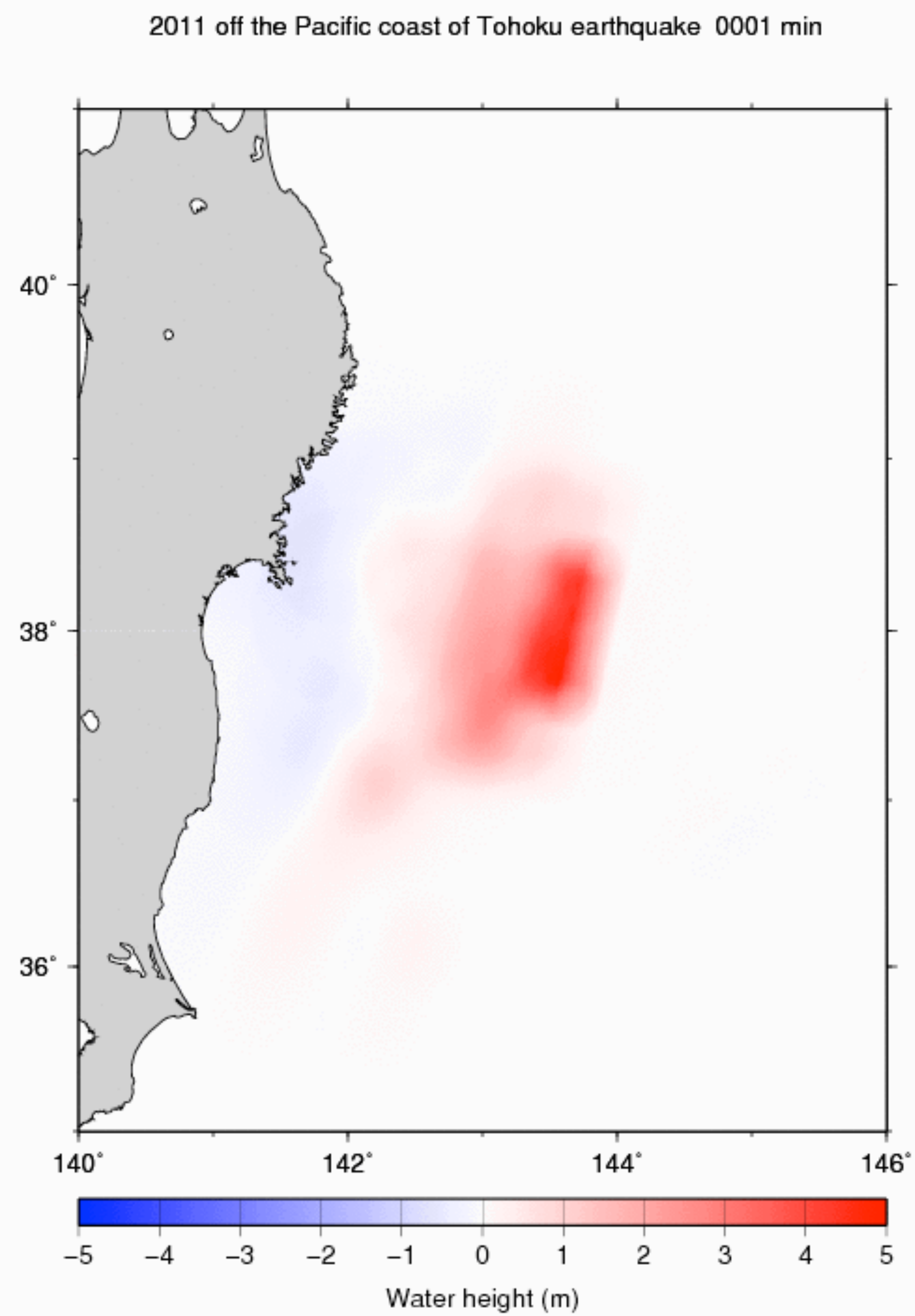
Northern sanriku – comparison with the tsunami in Meiji period and Showa period



Southern Sanriku

By: Dr.Tsuji, Dr.Satake, Project Researcher: Ishibe, Project Researcher: Nishiyama

Tsunami data and simulations: source

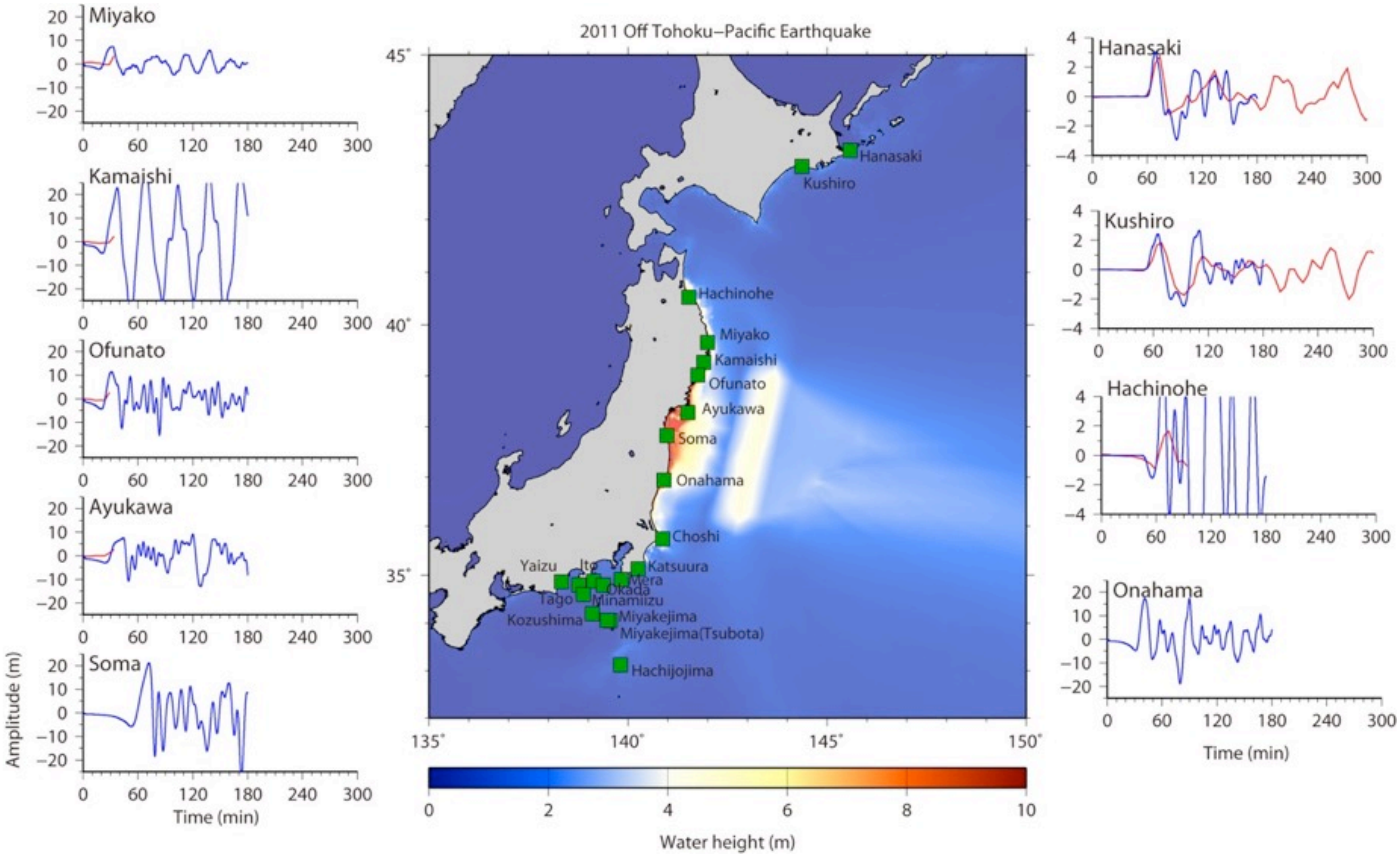


Tsunami Propagation

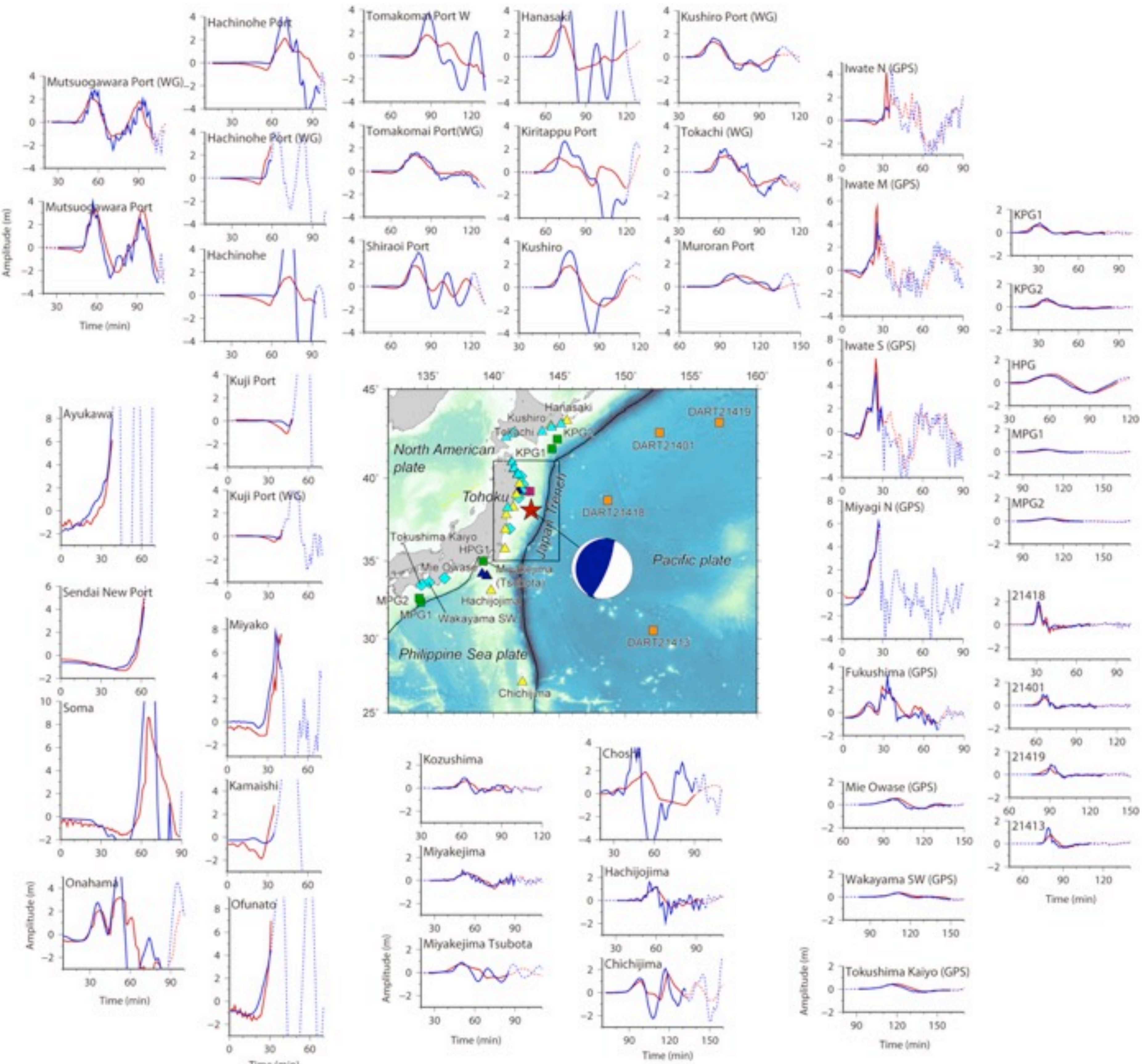
The red color means that the water surface is higher than normal sea level, while the blue means lower.

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

Tsunami data and simulations



Tsunami data and simulations: source

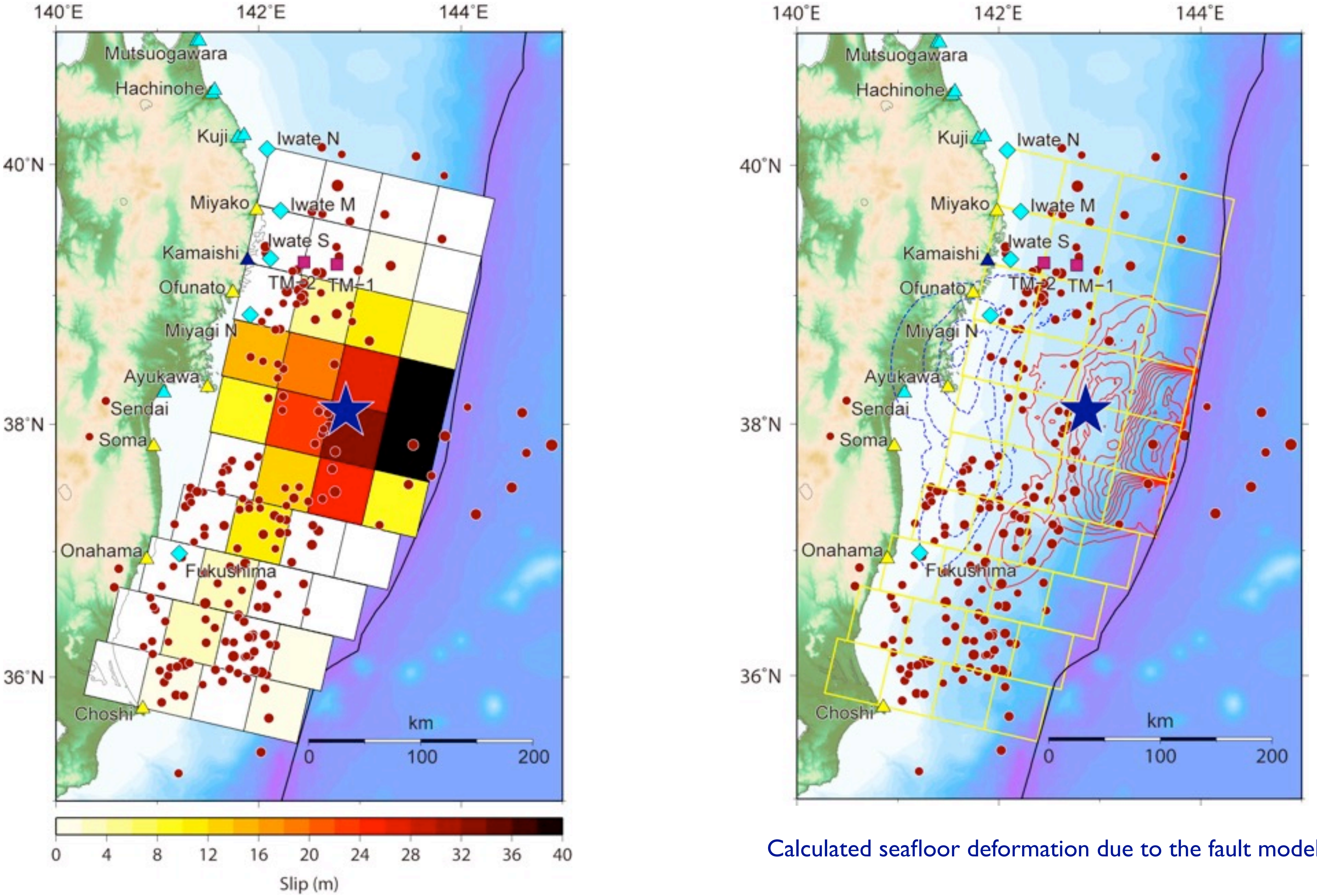


Simulated Tsunami around Japanese coasts

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.

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

Tsunami data and simulations: source



Slip distribution on the fault mode

Calculated seafloor deformation due to the fault model

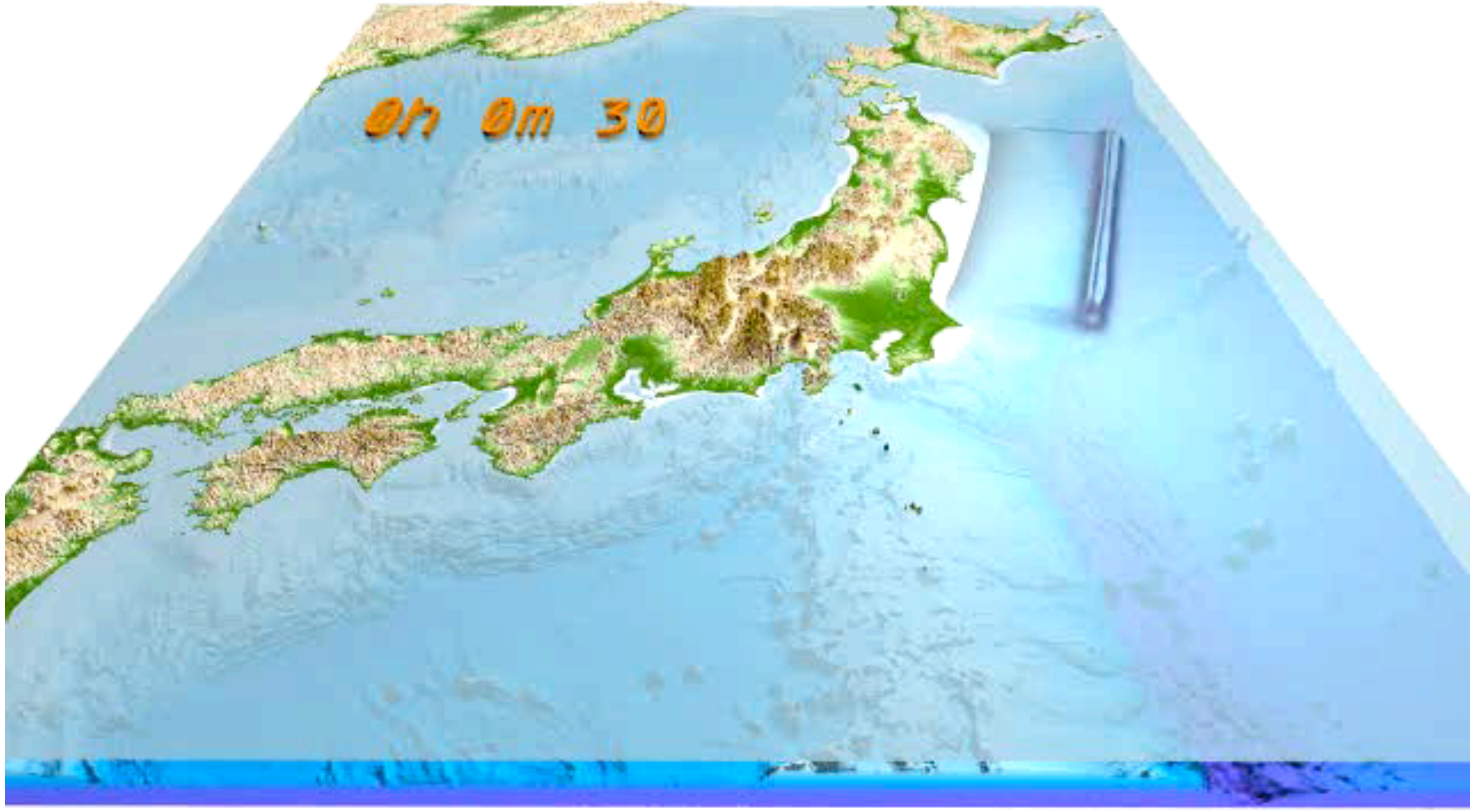
by Yushiro Fujii (IISEE, BRI) and Kenji Satake (ERI, Univ. of Tokyo)
http://iisee.kenken.go.jp/staff/fujii/OffTohokuPacific2011/tsunami_inv.html

Tsunami animation: time scales...

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

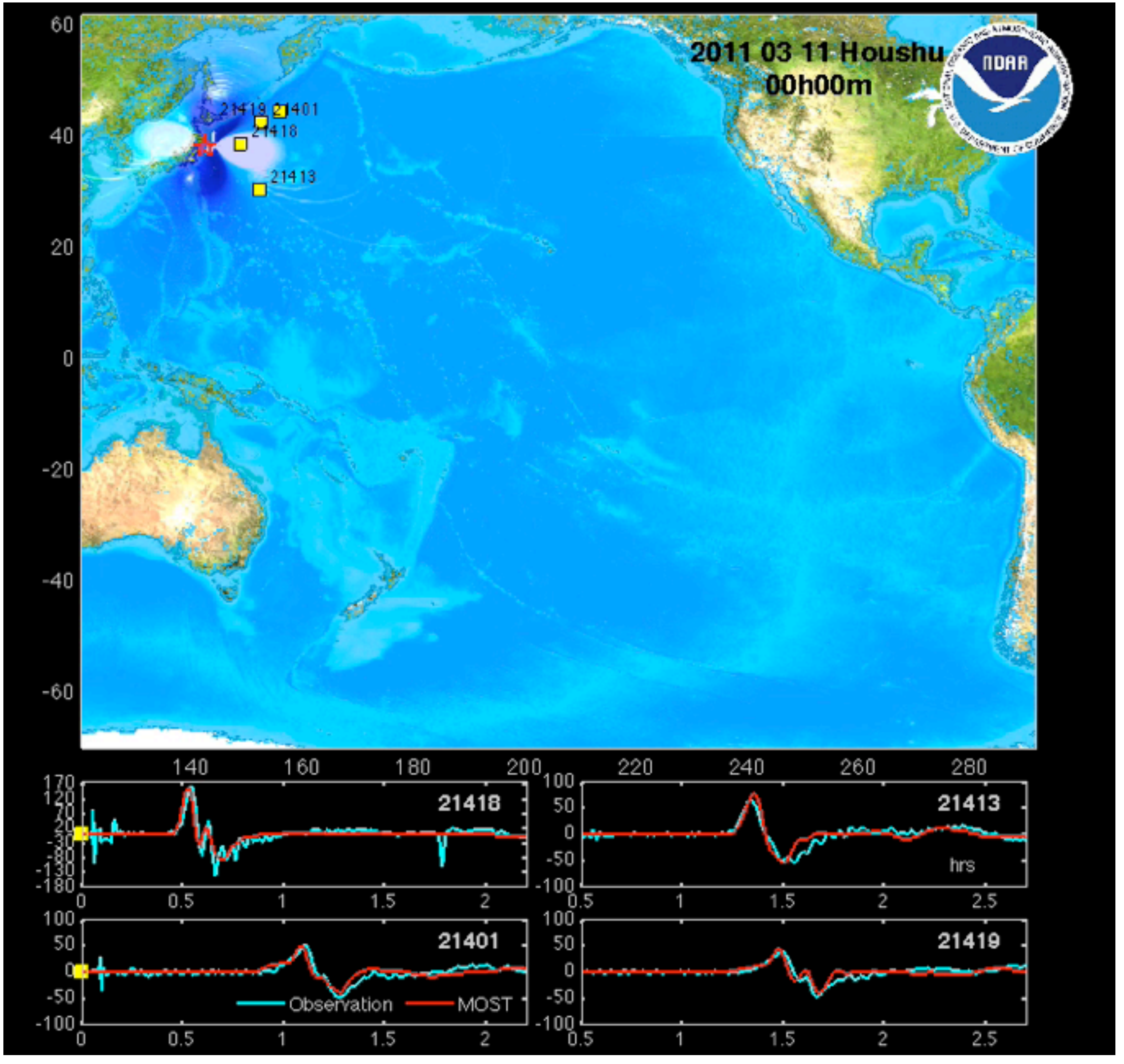
http://supersites.earthobservations.org/honshu.php

http://eqseis.geosc.psu.edu/~cammon/Japan2011EQ/

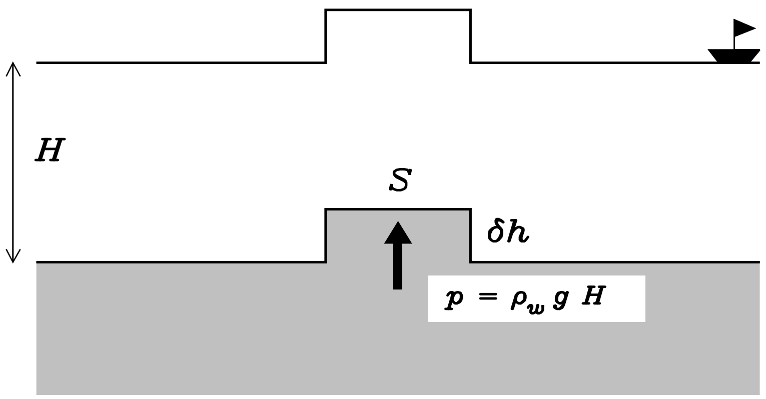


"Earthquake Research Institute, University of Tokyo, Prof. Takashi Furumura and Project Researcher Takuto Maeda"

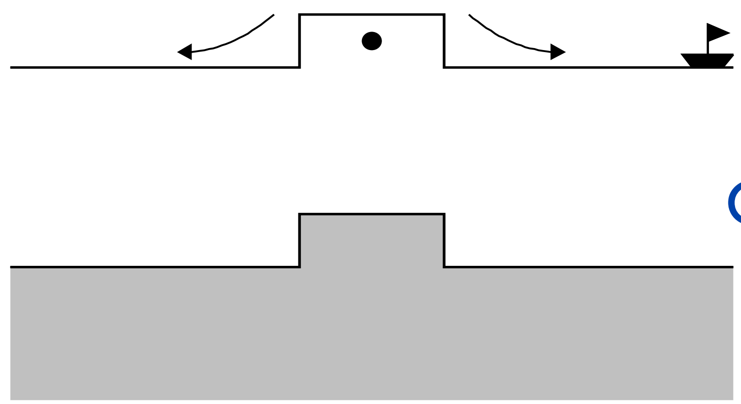
Tsunami animation - NOAA



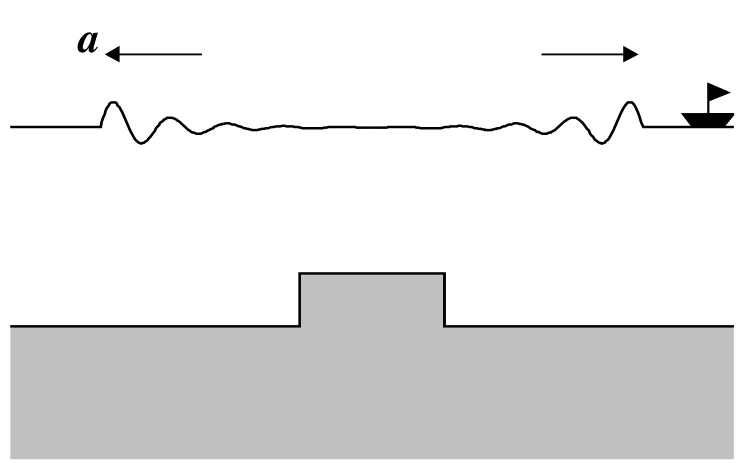
Very basic tsunami physics...



Bottom uplift
&
Waterberg
formation



Center of mass falls...



Potential
energy goes to
tsunami energy

Energy

$$E_R \approx 4.8 + 1.5M$$

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

$$L \sim 10^6 m;\ \lambda \sim 10^4 m;\ \delta h \sim 5m$$

$$E_R \approx 10^{18} J \geq 10^2 E_T$$

Wavelength

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

$$\lambda >> H >> a$$

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

Navier-Stokes equations

Newton's law + Conservation of matter + Viscosity

$$\rho\frac{\partial \mathbf{v}}{\partial t}+\rho(\mathbf{v}\cdot grad)\mathbf{v}=-grad(P)-\rho grad(\phi)+$$
$$+\eta\Delta\mathbf{v}+(\eta+\eta')grad\left(div(\mathbf{v})\right)$$

and in the incompressible case...

$$\frac{\partial \Omega}{\partial t}+rot(\Omega\times\mathbf{v})=\frac{\eta}{\rho}\Delta\Omega$$

Gravity waves: dispersion

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

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

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

deep water (kh goes to infinity)

$$\omega^2 = kg$$

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

$$u = \frac{\partial\omega}{\partial k} = \frac{1}{2}c = \frac{1}{2}\sqrt{\frac{g}{k}} = \frac{1}{2}\sqrt{\frac{g\lambda}{2\pi}}$$

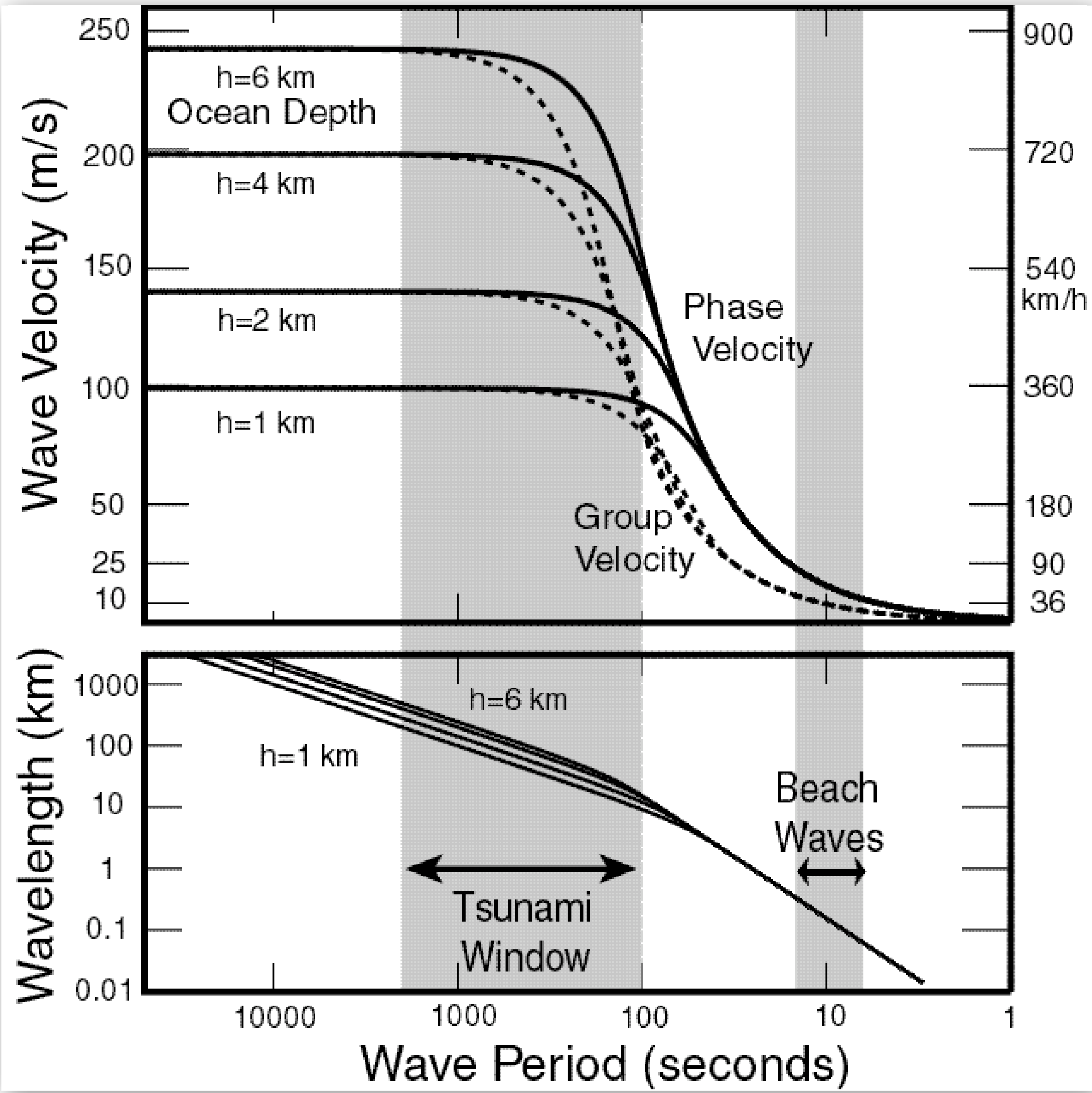
shallow water (kh goes to zero)

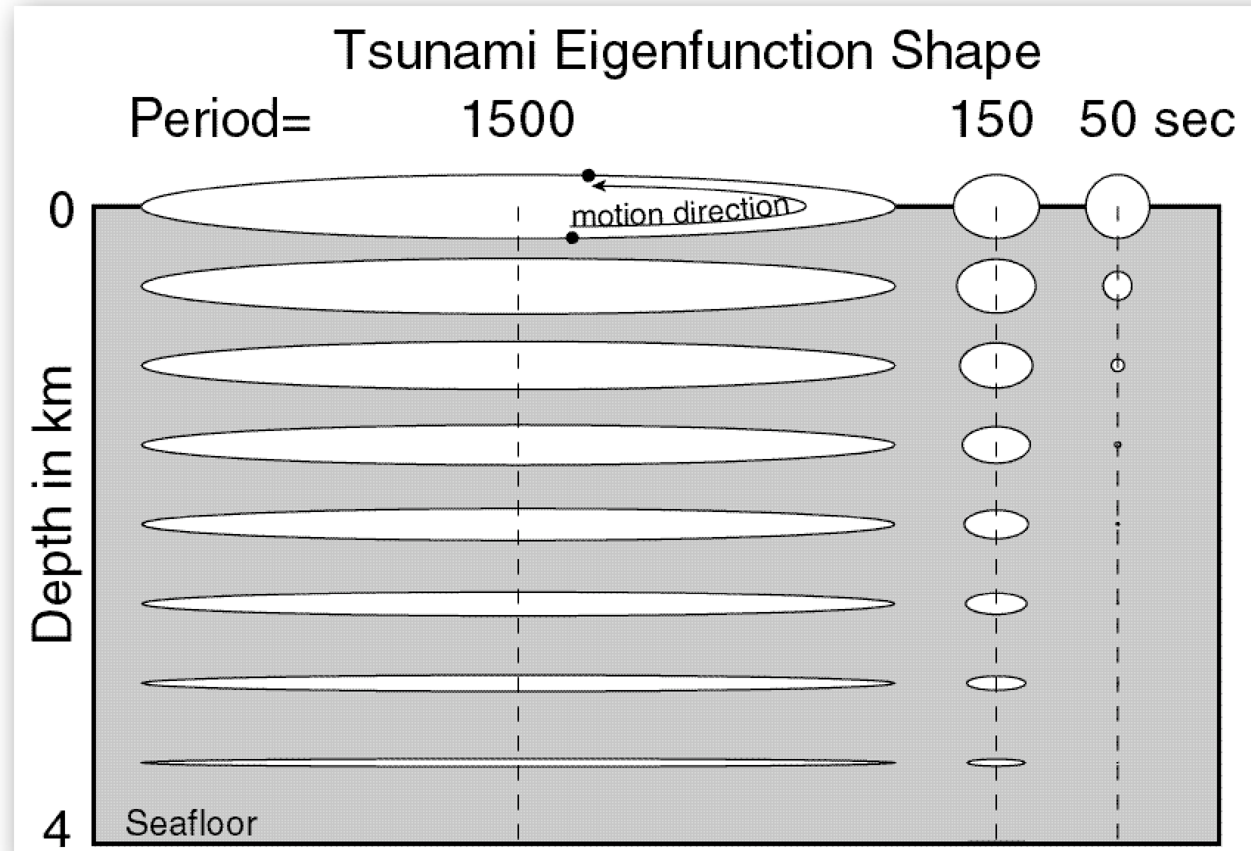
$$\omega^2 = k^2 gh$$

$$c = \sqrt{gh}$$

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

Tsunami eigenvalues & eigenfunctions





Dispersion & Non linearity

The dynamics of water waves in shallow water is described mathematically by the Korteveg - de Vries (KdV) equation

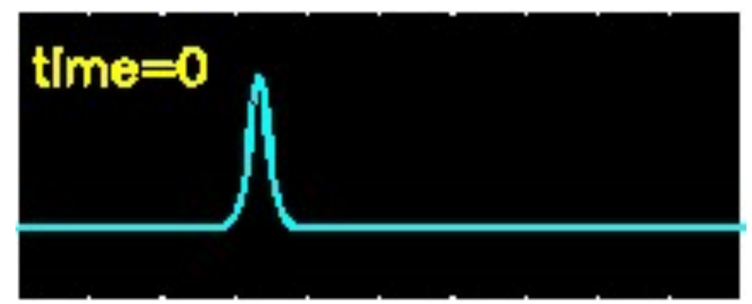
$u=u(x,t)$ measures the elevation at time t and position x, i.e. the height of the water above the equilibrium level

Dispersive term

$$u_t + u_{xxx} = 0$$

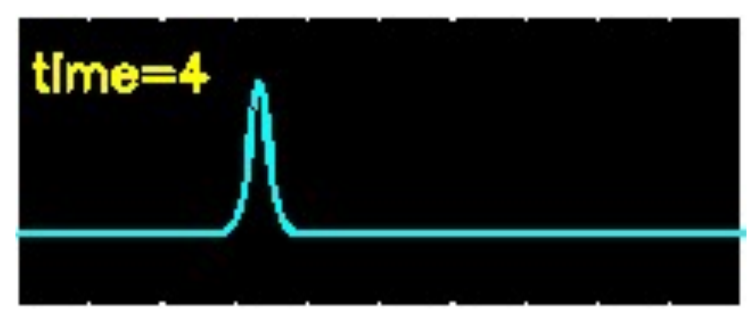
Nonlinearity

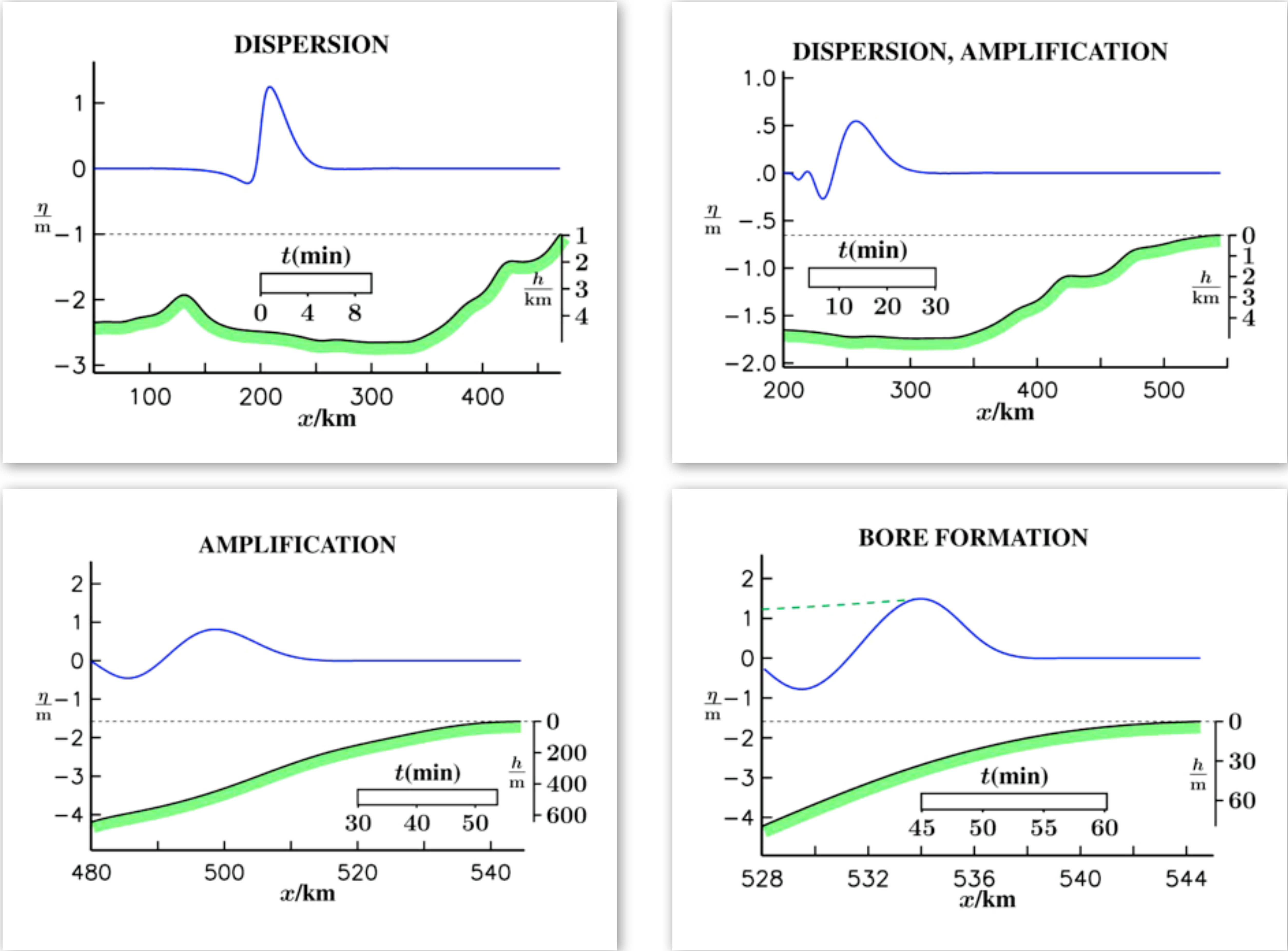
$$u_t + u\, u_x = 0$$



KdV

$$u_t + u_{xxx} + u\, u_x = 0$$





DISPERSION
1
0
η/m −1
−2
−3
t(min)
0 4 8
h/km
1
2
3
4
100 200 300 400
x/km
DISPERSION, AMPLIFICATION
1.0
.5
.0
η/m −.5
−1.0
−1.5
−2.0
t(min)
10 20 30
h/km
0
1
2
3
4
200 300 400 500
x/km
AMPLIFICATION
2
1
0
η/m −1
−2
−3
−4
t(min)
30 40 50
h/m
0
200
400
600
480 500 520 540
x/km
BORE FORMATION
2
1
0
η/m −1
−2
−3
−4
t(min)
45 50 55 60
h/m
0
30
60
528 532 536 540 544
x/km

Modal approach - sketch

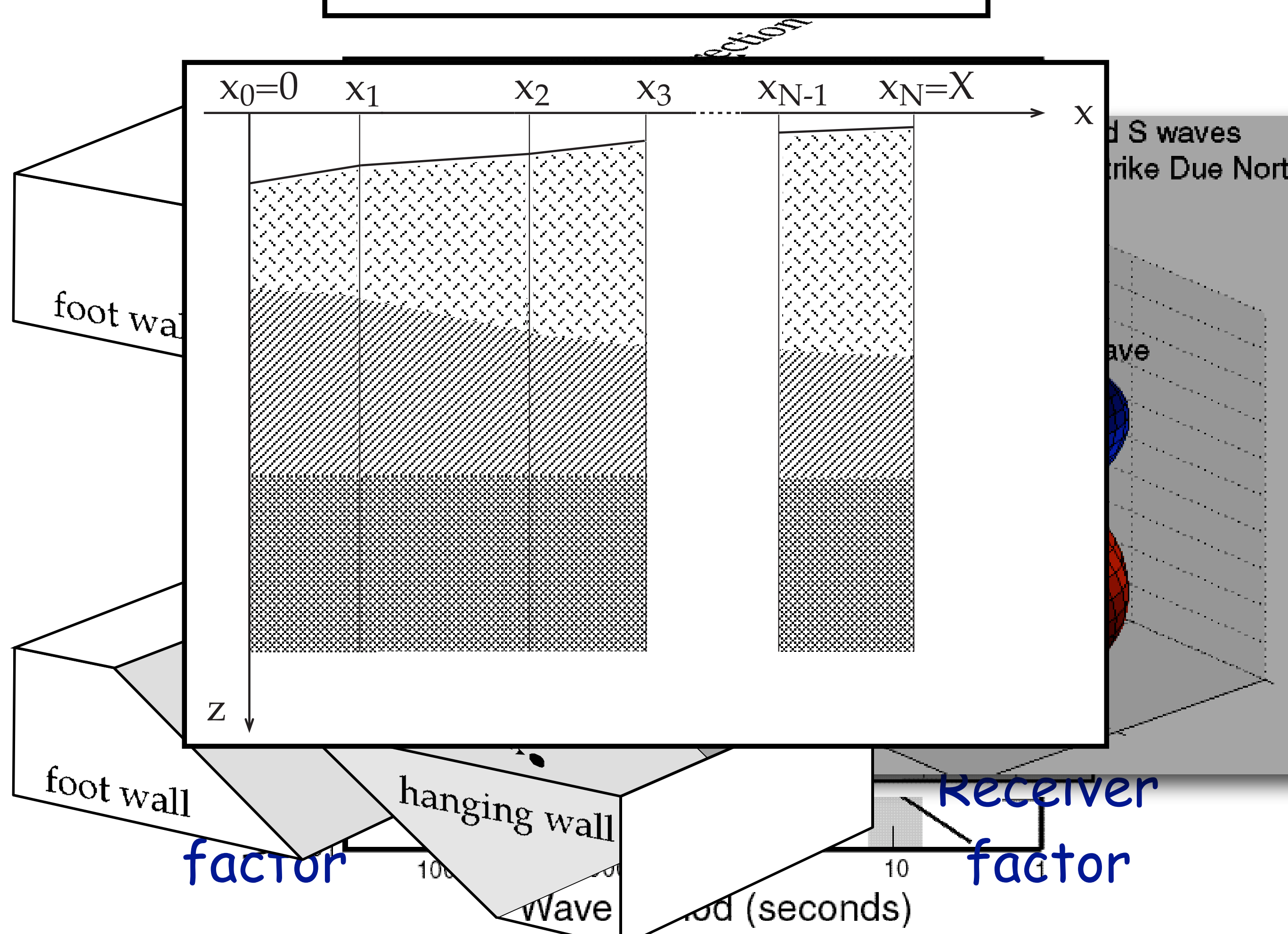
Equations of elastic motion with gravity + boundary conditions

FULL coupling between the fluid and solid layers

Eigenvalues
&
Eigenfunctions

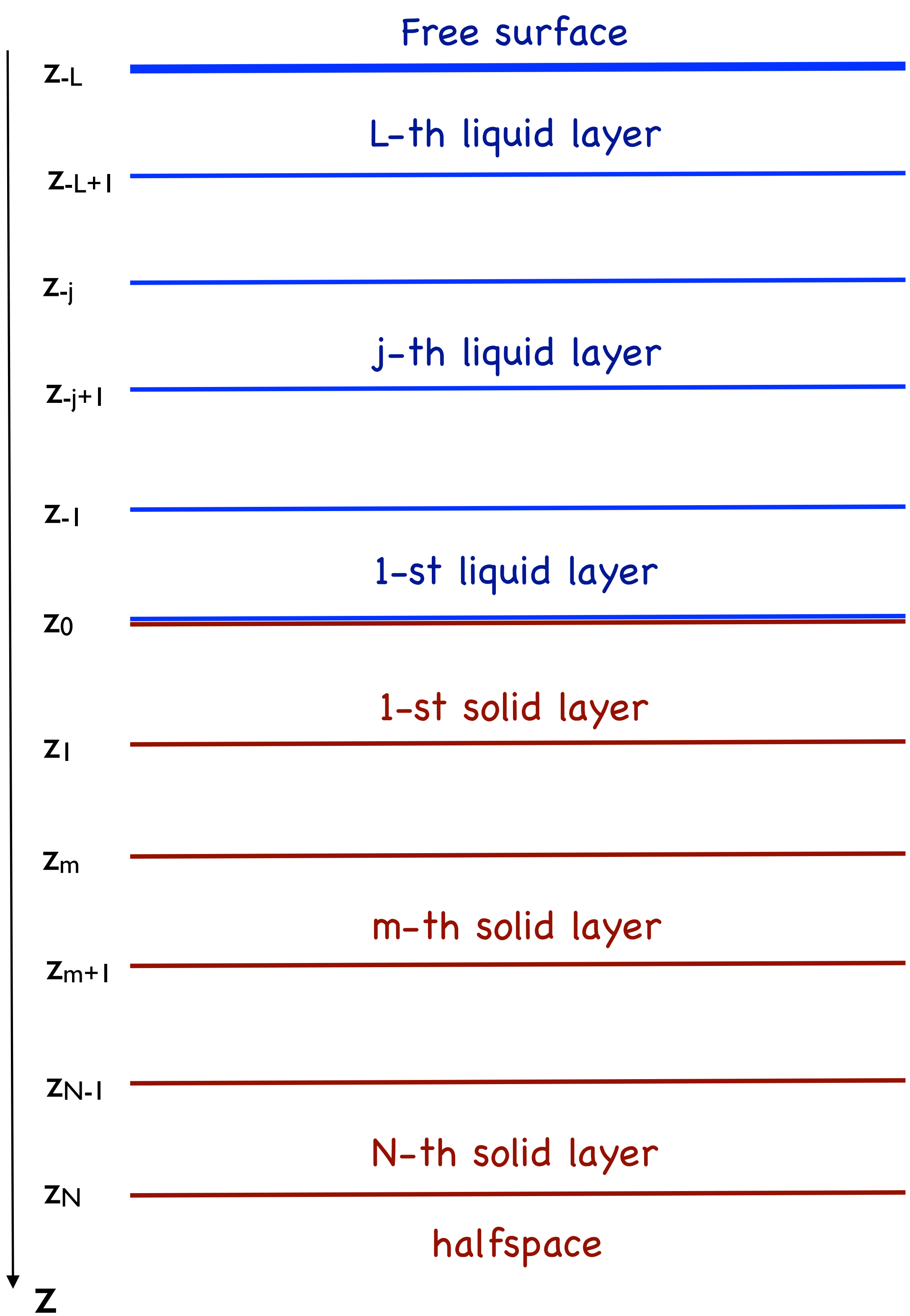
Seismic source excitation

Tsunami mode propagation in LHM



$$U(X,\varphi,z,\omega,t) = \frac{\exp(-i\pi/4)}{\sqrt{8\pi}} \frac{\exp[i\omega(t-\tau)]}{\sqrt{J}} \left.\frac{\chi(h_s,\varphi)R(\omega)}{\sqrt{\omega c}\sqrt{v_g I_1}}\right|_s \left.\frac{u(z,\omega)}{\sqrt{v_g I_1}}\right|_X$$

Modal approach: formulation



Equations of motion | **Boundary conditions**

$$\alpha^2\nabla\left(\nabla \bullet \mathbf{u}\right) - gw = 0$$

$$w_{-j}\left(z_{-j}\right) = w_{-j-1}\left(z_{-j}\right); u_{-j}\left(z_{-j}\right) = u_{-j-1}\left(z_{-j}\right)$$

$$p_{-j}\left(z_{-j} + w_{-j}\right) = p_{-j-1}\left(z_{-j} + w_{-j-1}\right)$$

$$\partial_t^2 \mathbf{u} = \alpha^2\nabla\left(\nabla \bullet \mathbf{u}\right) - g\left(\nabla \bullet \mathbf{u}\right)$$

$$w_{-1}\left(z_0\right) = w_1\left(z_0\right)$$

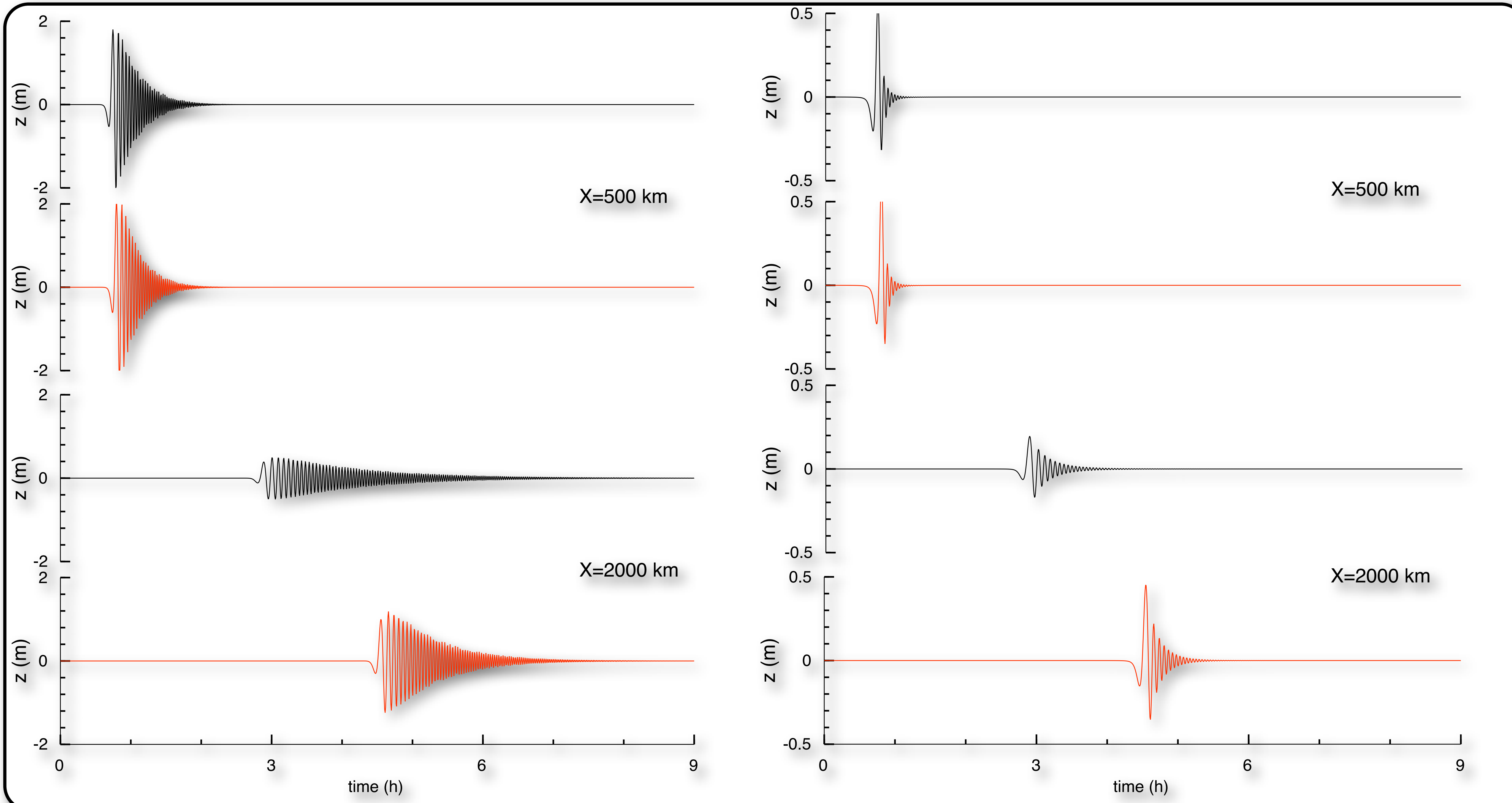
$$p_{-1}\left(z_0\right) = \sigma_1\left(z_0\right); 0 = \tau_1\left(z_0\right)$$

$$\partial_t^2 \mathbf{u} = \alpha^2\nabla\left(\nabla \bullet \mathbf{u}\right) - \beta^2\nabla \times \left(\nabla \times \mathbf{u}\right) - g\left(\nabla \bullet \mathbf{u}\right)$$

$$w_m\left(z_m\right) = w_{m+1}\left(z_m\right); u_m\left(z_m\right) = u_{m+1}\left(z_m\right)$$

$$\sigma_m\left(z_m\right) = \sigma_{m+1}\left(z_m\right); \tau_m\left(z_m\right) = \tau_{m+1}\left(z_m\right)$$

Example: synthetic signals for the tsunami mode (vertical component) excited by a dip-slip mechanism with M_0=2.2 10^{21} Nm. h_s = 14 km; h_s = 34 km.

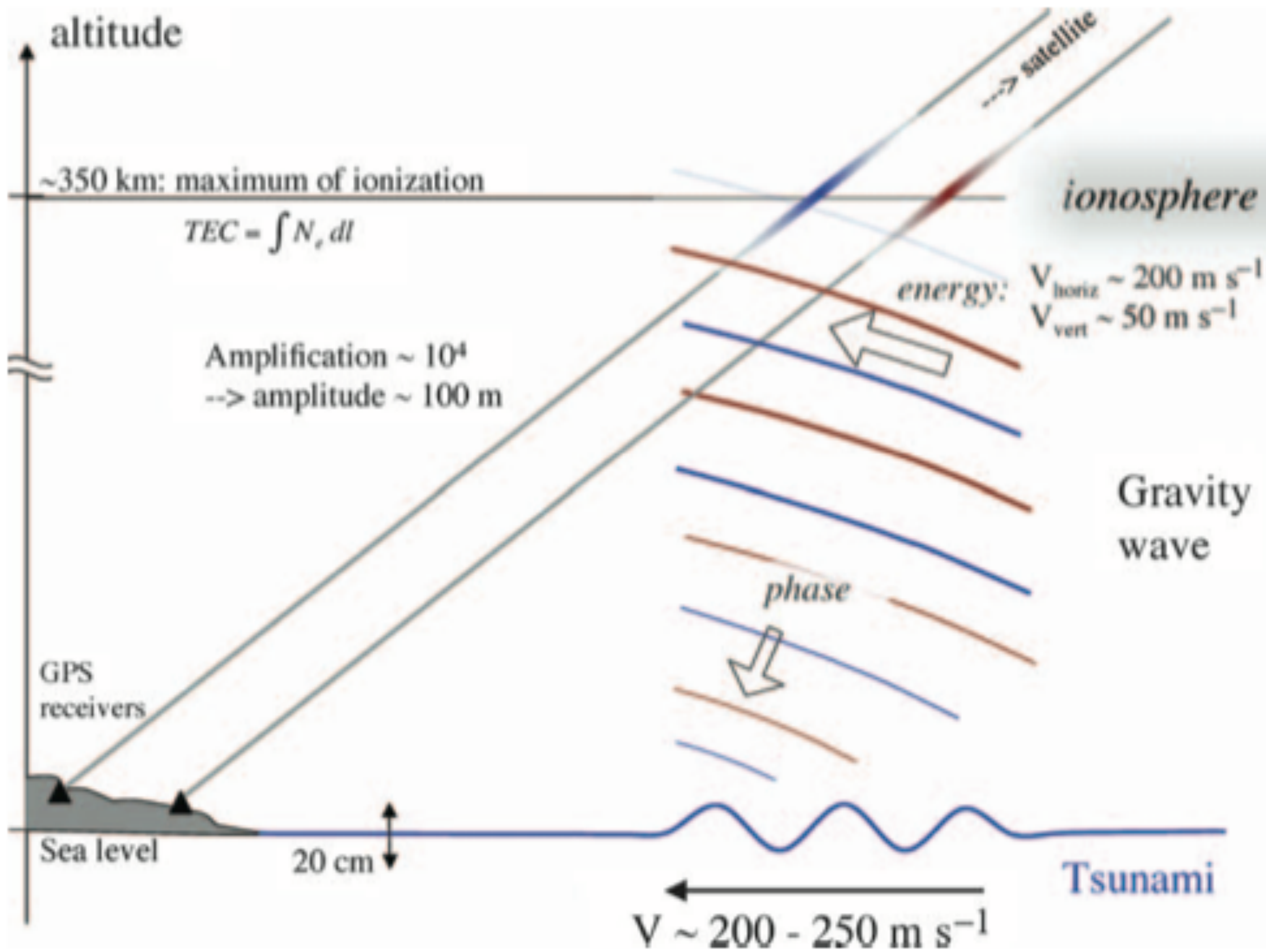


For each of the two source-receiver distances considered, the upper trace refers to the 1-D model and the lower trace to a laterally varying model. In the laterally varying model the liquid layer is getting thinner with increasing distance from the source, with a gradient of 0.00175 and the uppermost solid layer is compensating this thinning.

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

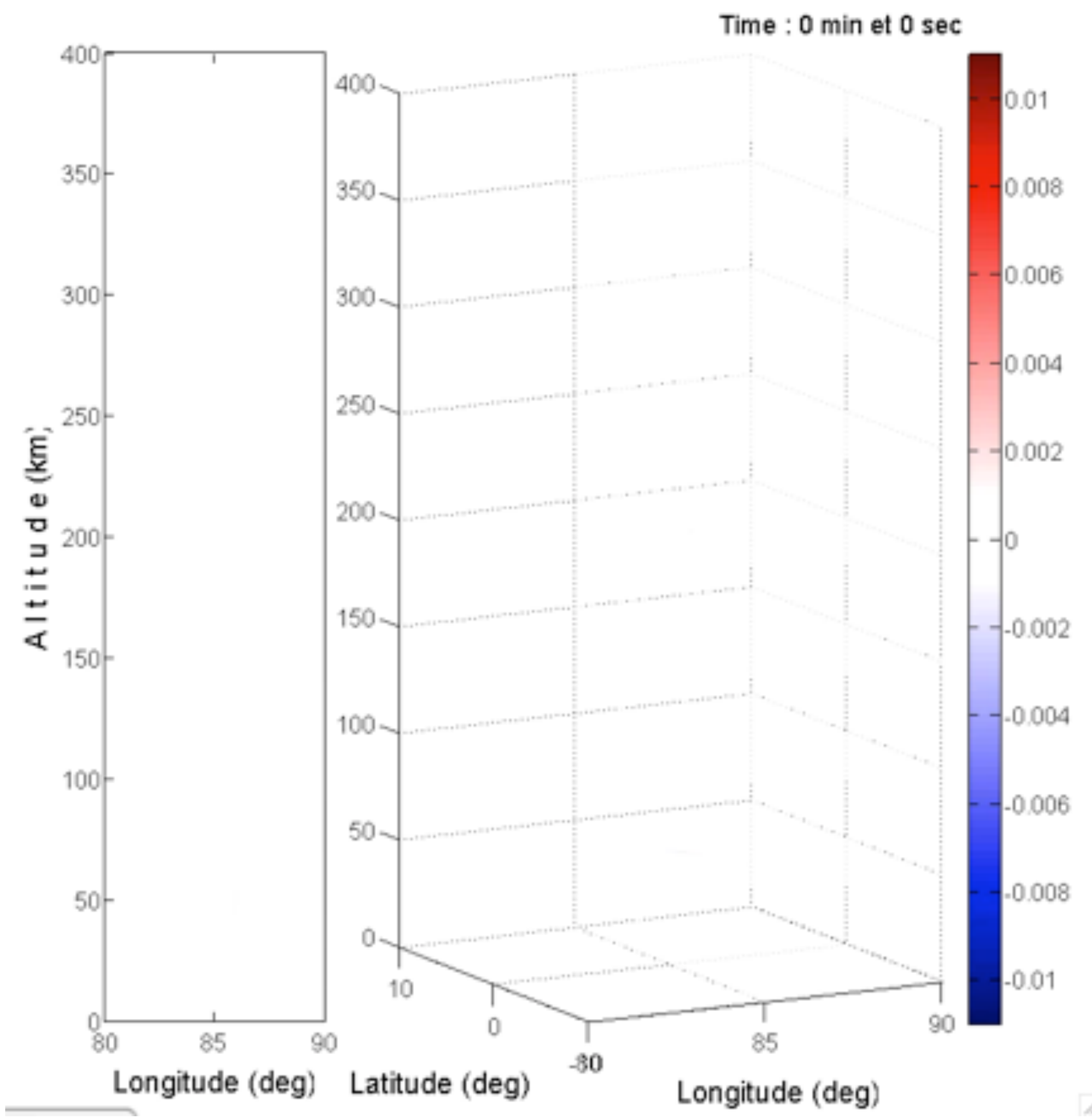
Artru et al. (2005): ionospheric imaging can detect tusnami signatures. GPS JAPAN net was used to map Chilean Tsunami of 2001

Occhipinti et al. (2006): Sumatra tsunami mapped

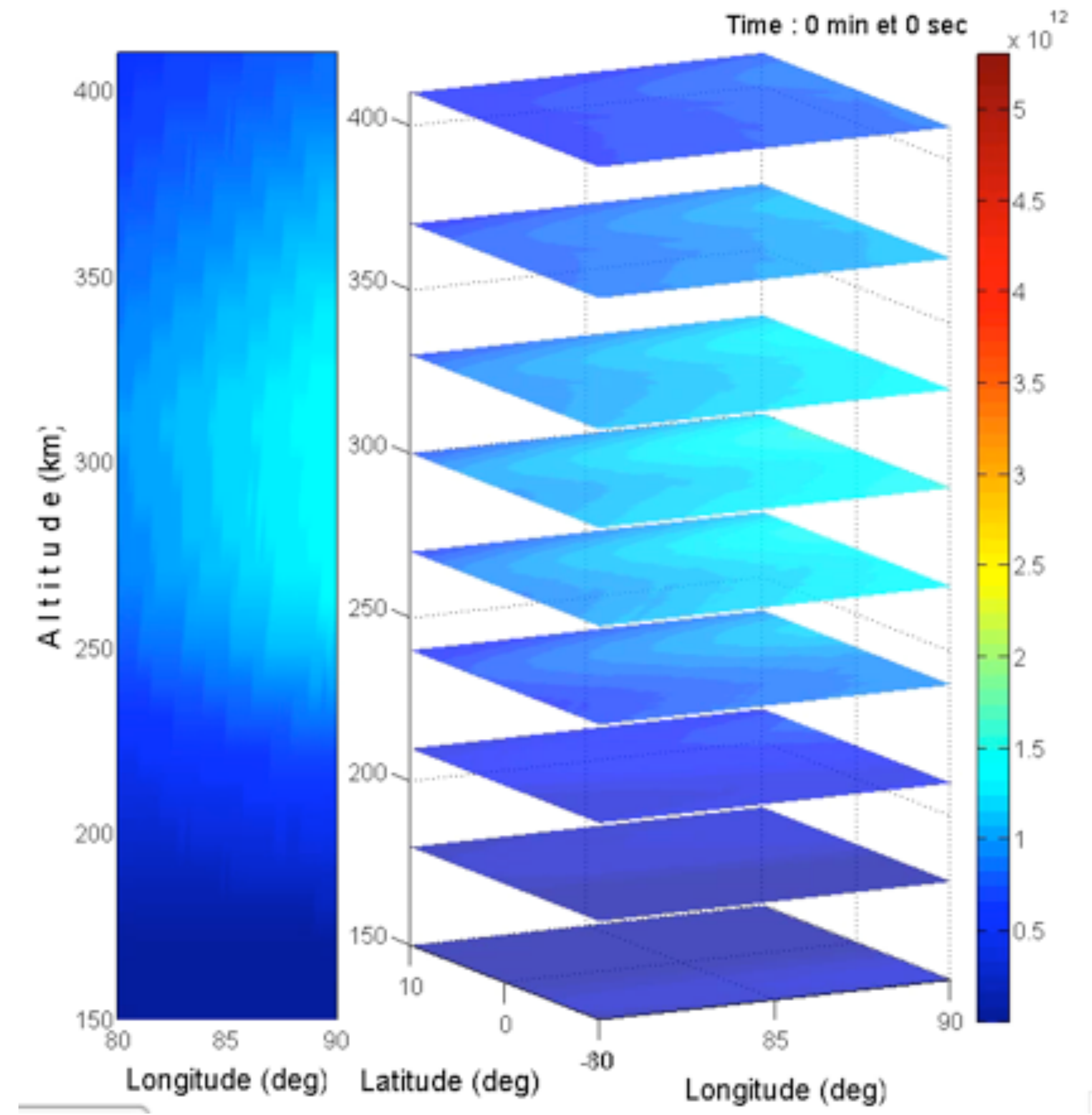
Three-dimensional waveform modeling of ionospheric signature
induced by the 2004 Sumatra tsunami
Giovanni Occhipinti, Philippe Lognonné, E. Alam Kherani and Helene Hebert
GRL, 2006, 33

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

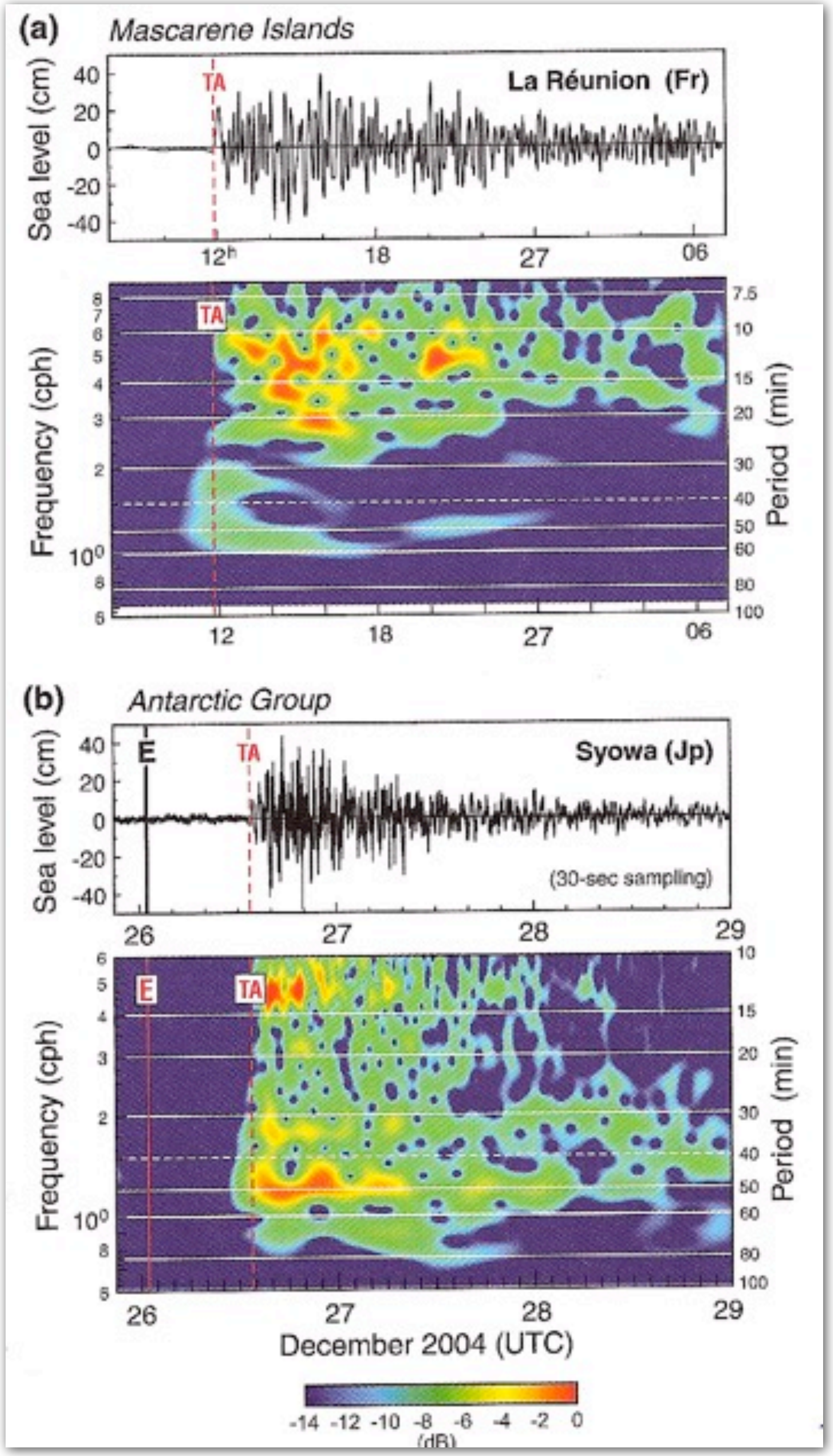
Measurement of tsunami waves

Tide gauges can measure TW along the coast...

Tsunami records and their f-t diagram: solid line (E) is the time of main shock, dashed line (TA) is Tsunami arrival

The 26 December 2004 Sumatra Tsunami: Analysis of Tide Gauge Data from the World Ocean Part 1. Indian Ocean and South Africa

Alexander B. Rabinovich and Richard E. Thomson



Measurement of tsunami waves

Tide gauges can measure TW along the coast, but their detection in open ocean is challenging, due to their wavelengths and amplitudes.

ocean bottom sensors

(pressure gauges & seismometers)

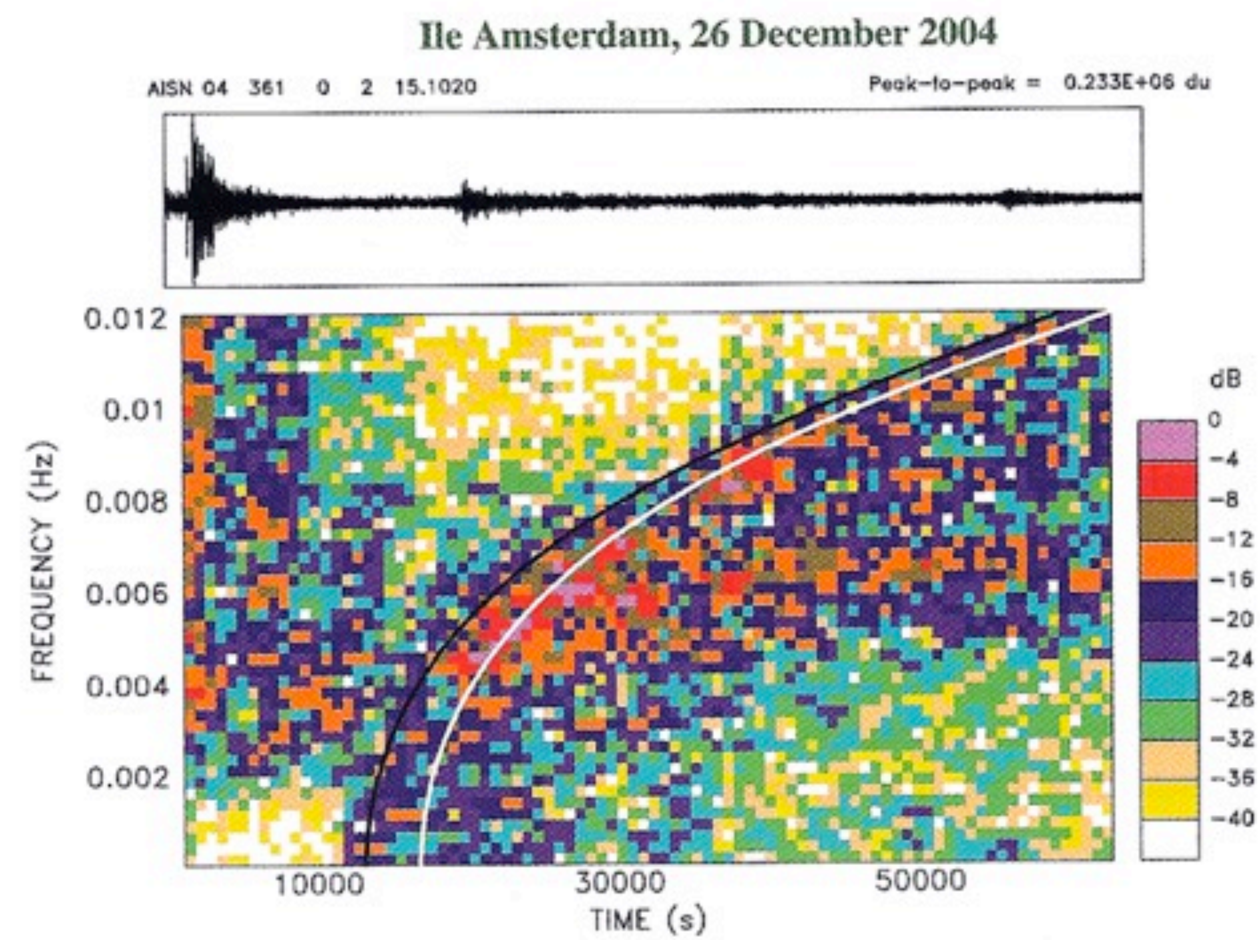


Figure 4

Spectrogram of the tsunami recording at AIS (Ile Amsterdam). The individual pixels identify the spectral amplitude present in the wave train as a function of time (abscissa) and frequency (ordinate), according to the logarithmic scale at right. In order to emphasize the high frequencies in the record, we processed the raw seismogram, without deconvolution of the instrument response. The black curve is the dispersion expected from equation (1) for a 4-km deep ocean basin and a source at the epicenter of rupture. The white curve uses a 3.5-km basin and places the source at the centroid of rupture (Tsai *et al.*, 2005).

Seismic Records of the 2004 Sumatra and Other Tsunamis: A Quantitative Study

Emile A. Okal

Measurement of tsunami waves

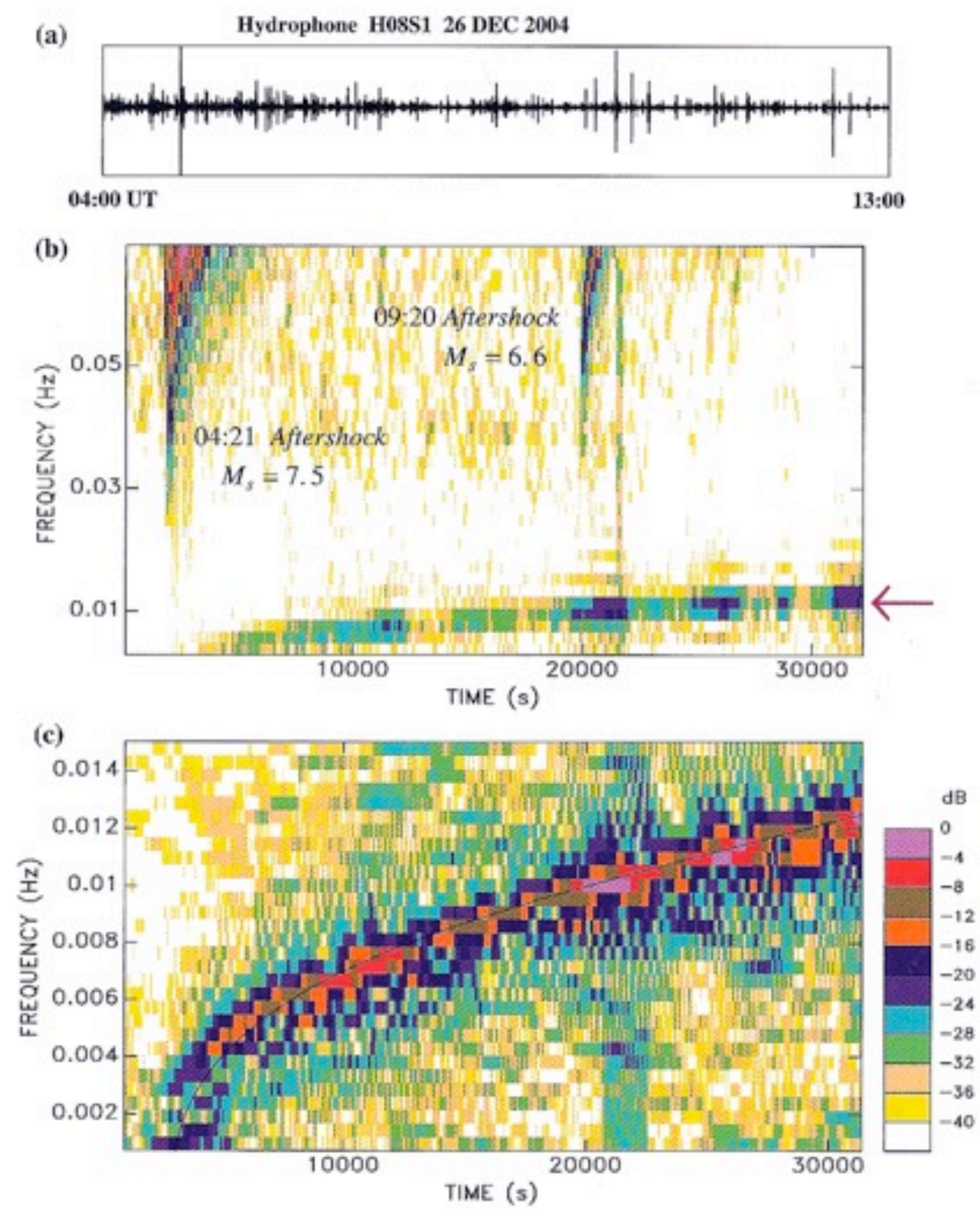
Tide gauges can measure TW along the coast, but their detection in open ocean is challenging, due to their wavelengths and amplitudes.

ocean bottom sensors

hydrophones
(towards "high" frequency bands...)

a) Raw time series
b) spectrogram
c) close-up of the tsunami branch and comparison with
w^2=gktanh(kH)

Quantification of Hydrophone Records of the 2004 Sumatra Tsunami
Emile A. Okal, Jacques Talandier and Dominique Reymond



Measurement of tsunami waves

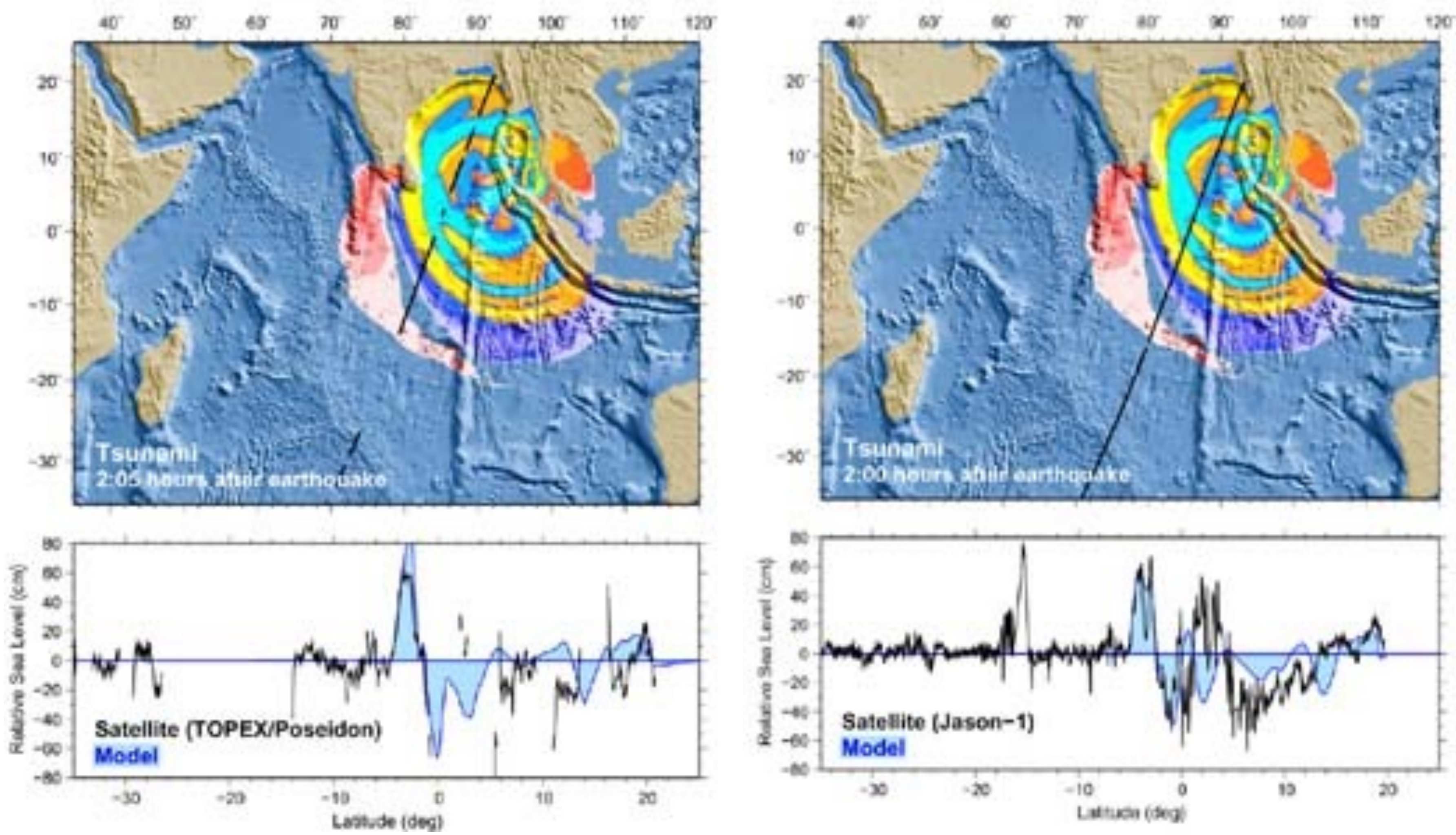
Tide gauges can measure TW along the coast, but their detection in open ocean is challenging, due to their wavelengths and amplitudes.

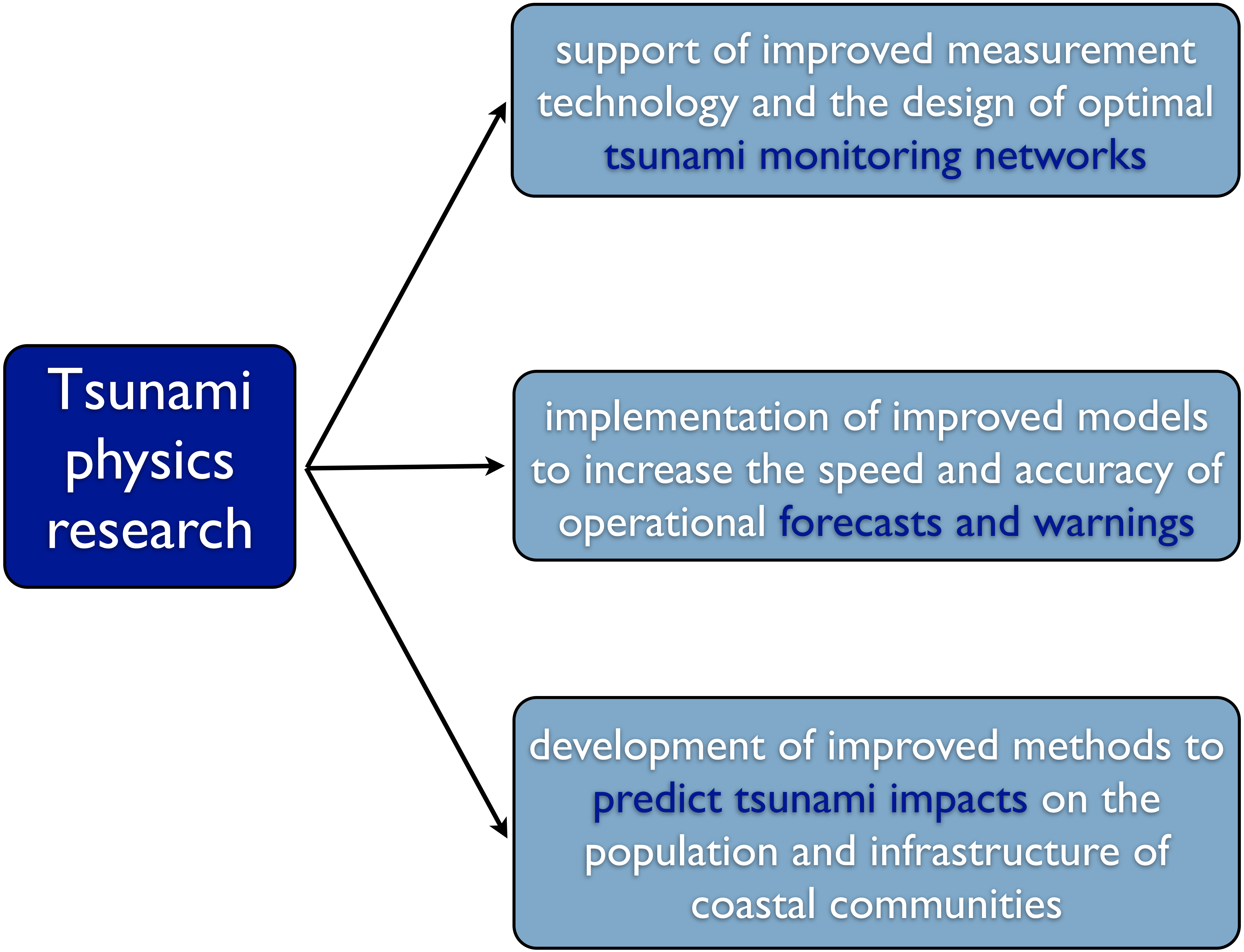
ocean bottom sensors (pressure gauges or seismometers)

sea level measurement (GPS receivers on buoys)

satellite altimetry

NOAA




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 modelling research

- Develop numerical models for faster and more reliable forecasts of tsunamis propagating through the ocean and striking coastal communities.
- Provide assistance to the Tsunami Warning Centers (TWC) in the form of Forecast Modeling software products specifically designed to support the Tsunami Warning Center's forecasting operations.
- Inundation Modeling to assist coastal communities in their efforts to assess the tsunami hazard and mitigate the risk.

Tsunami forecast model

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

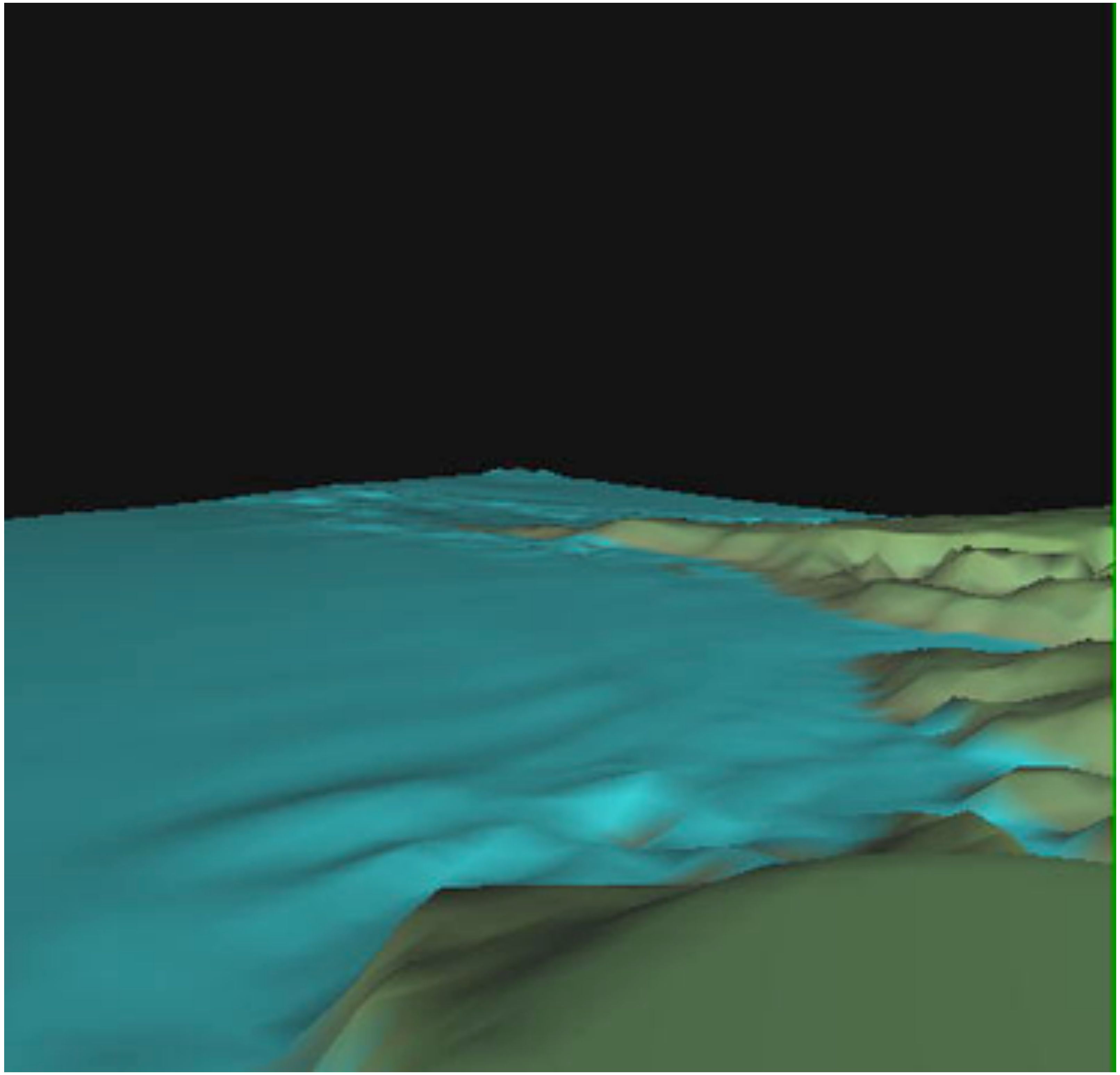
Arrival time
Height
Inundation area

↓ Inundation modelling

Inundation maps

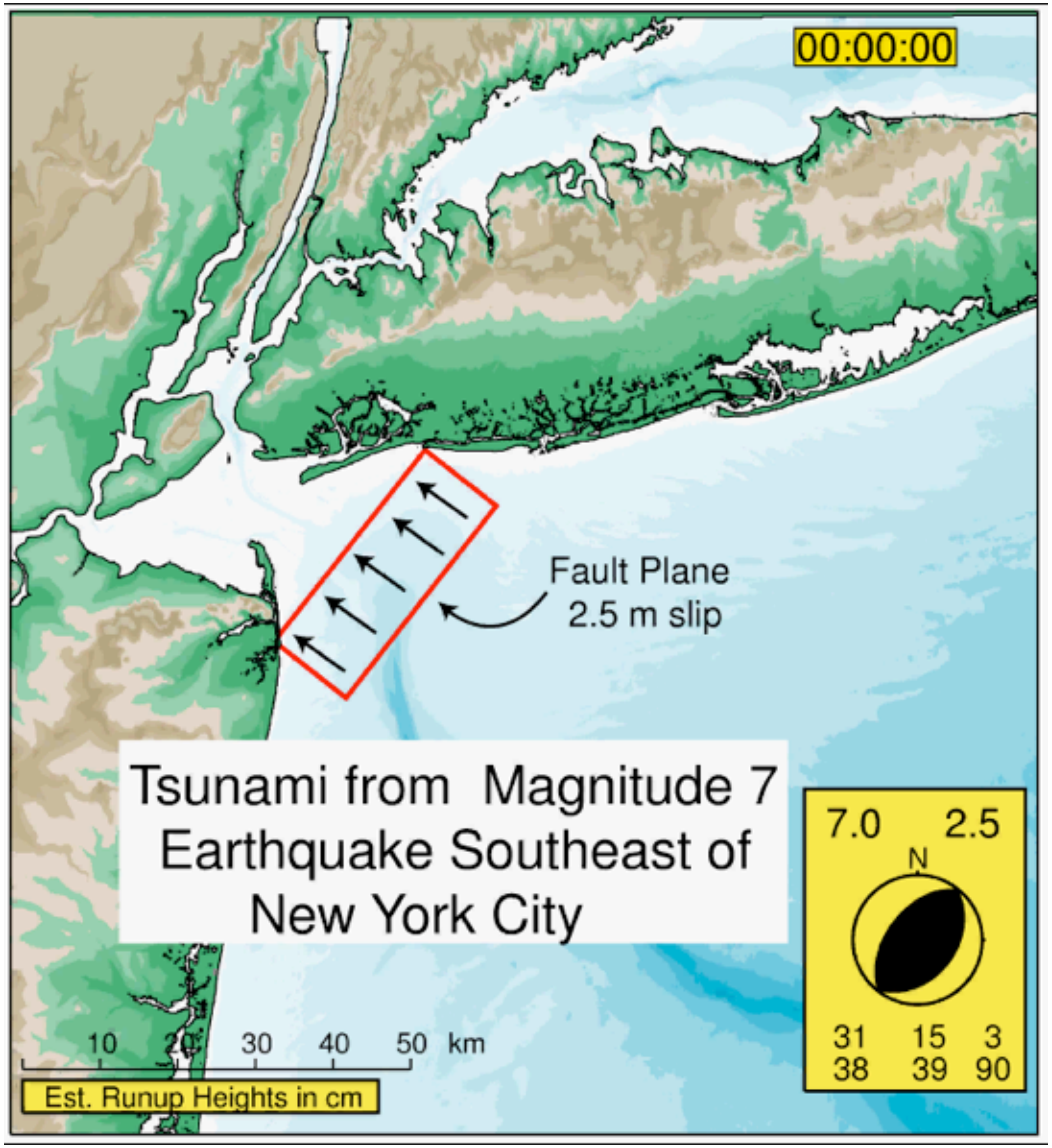
maximum wave height and maximum current speed as a function of location, maximum inundation line, as well as time series of wave height at different locations indicating wave arrival time

Inundation of the Aonae peninsula during the July 12, 1993 Hokkaido-Nansei-Oki tsunami computed with the MOST inundation model.



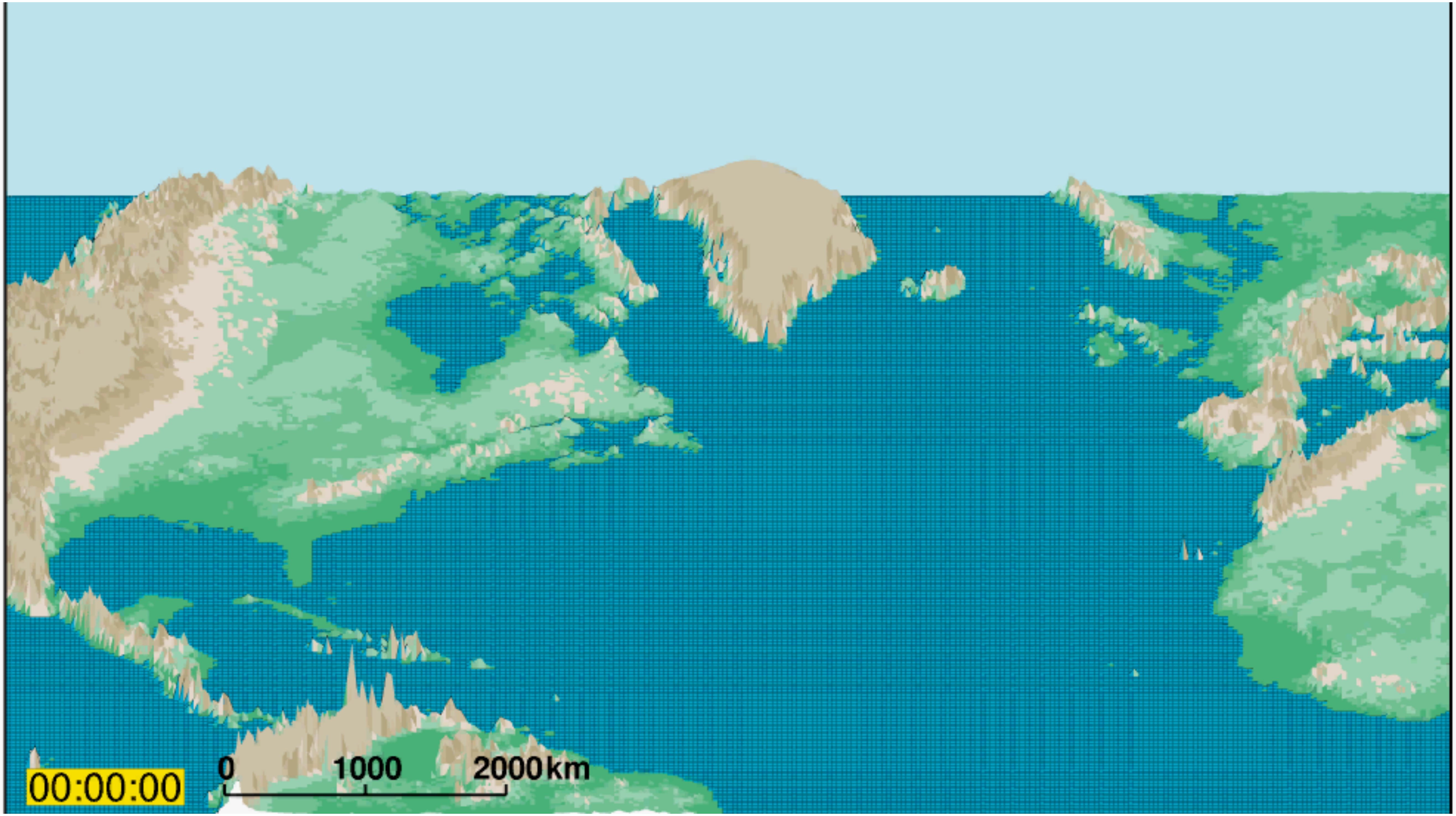
http://nctr.pmel.noaa.gov/model.html

New York City Tsunami from M7 Quake



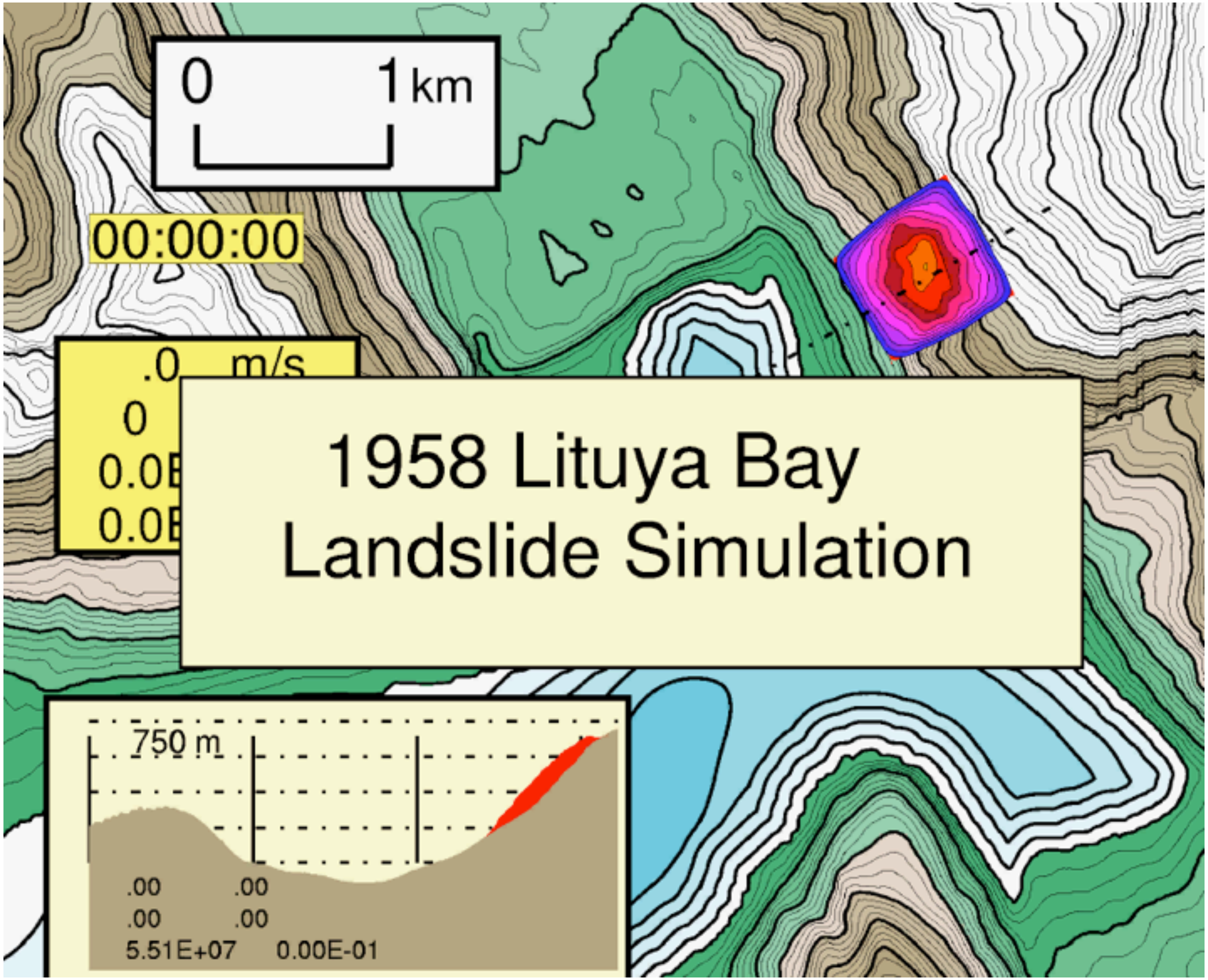
Courtesy of Steven Ward: http://www.es.ucsc.edu/~ward/

Atlantic Ocean Asteroid Tsunami Simulation - 3d



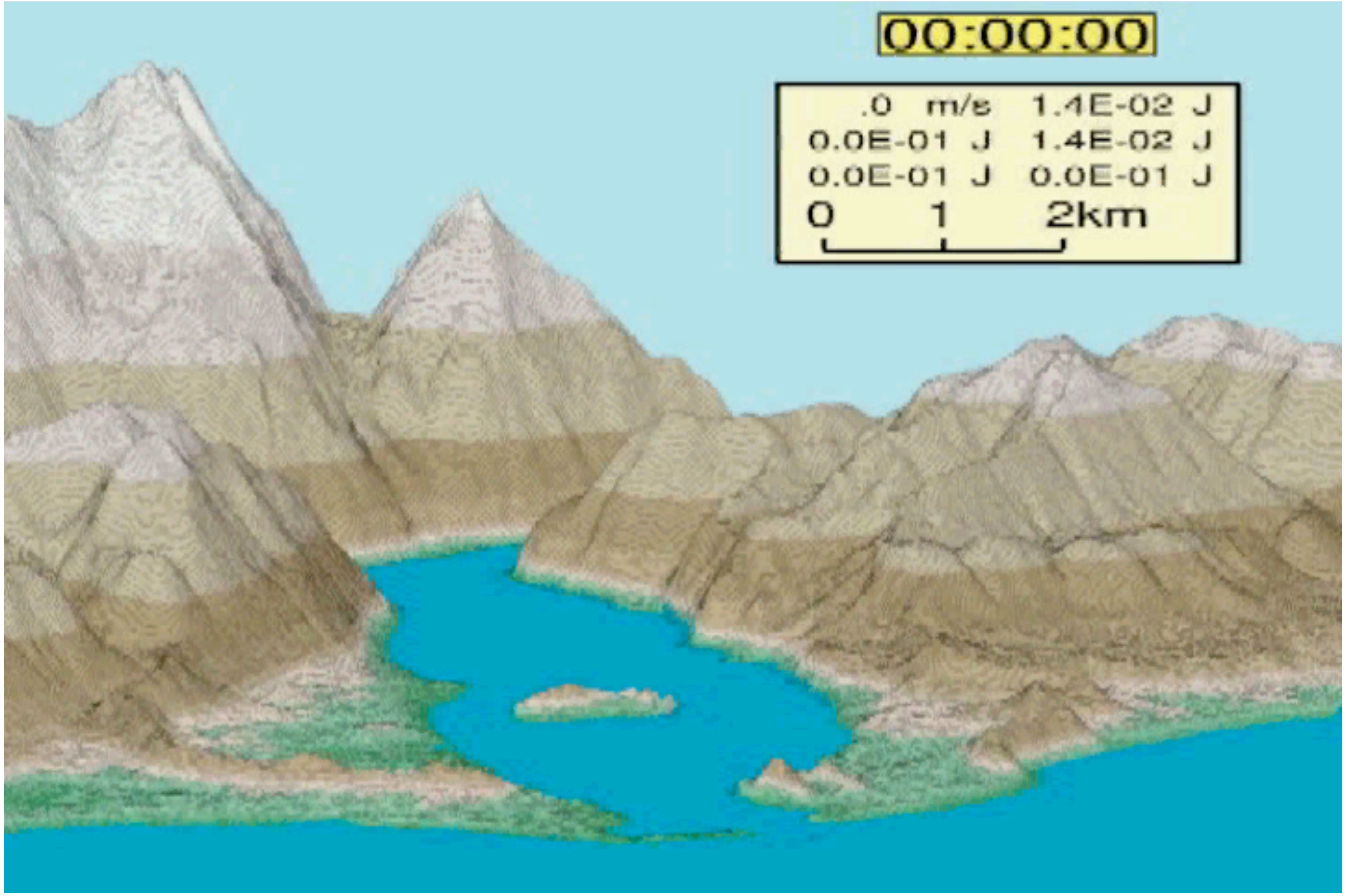
Courtesy of Steven Ward: http://www.es.ucsc.edu/~ward/

1958 Lituya Bay Landslide



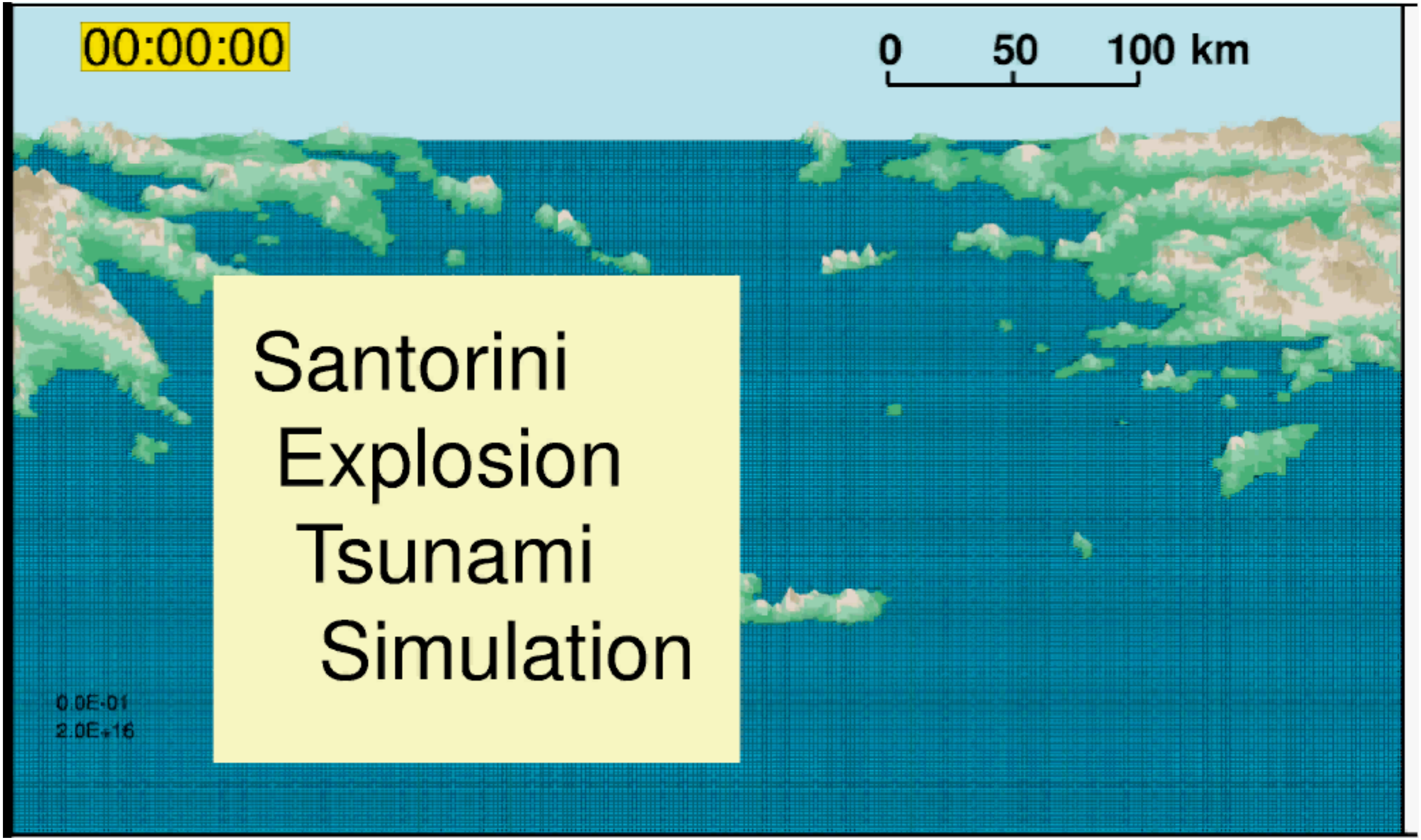
Courtesy of Steven Ward: http://www.es.ucsc.edu/~ward/

1958 Lituya Bay Landslide



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

Santorini Tsunami Simulation 3D



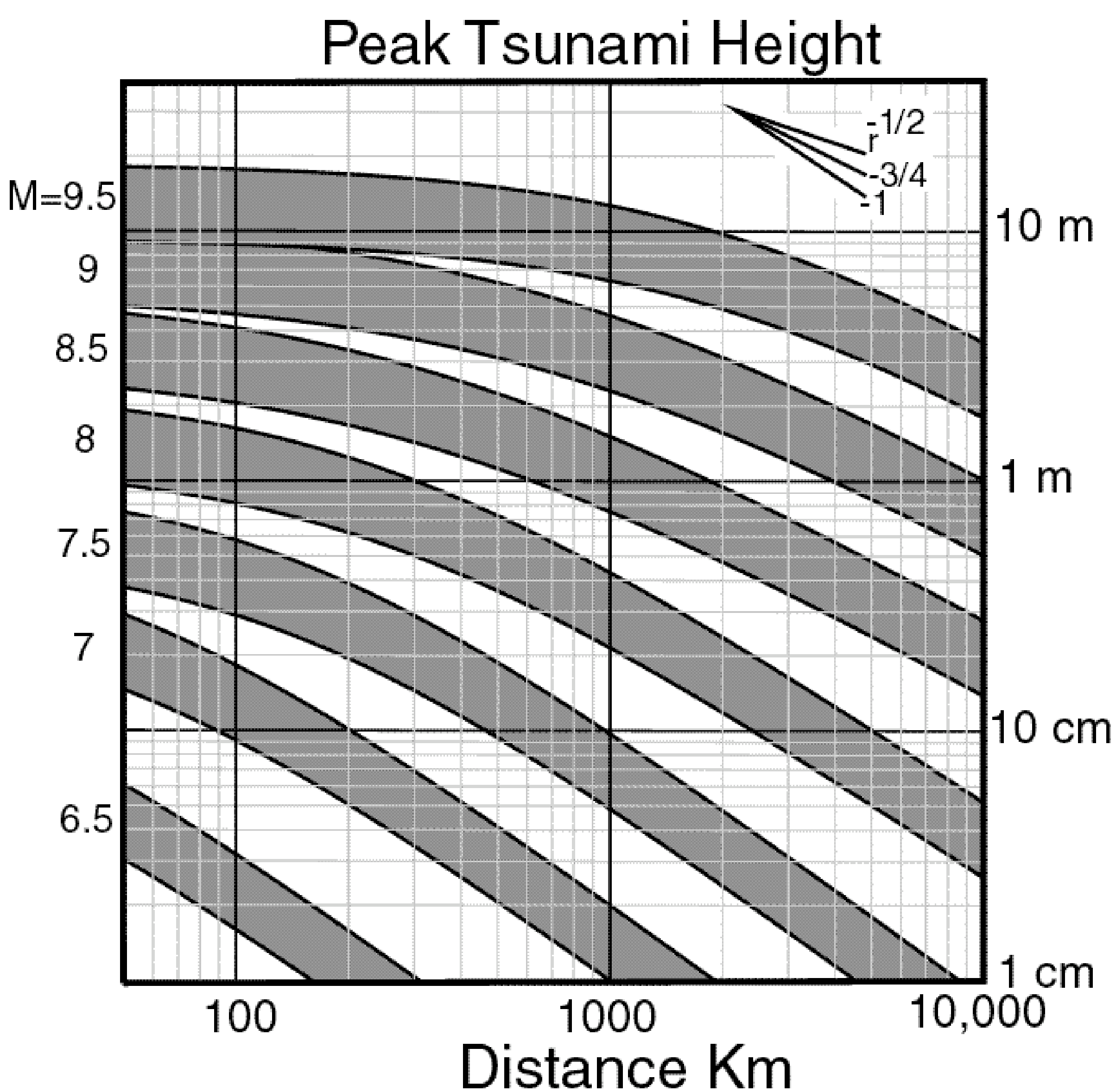
Courtesy of Steven Ward: http://www.es.ucsc.edu/~ward/

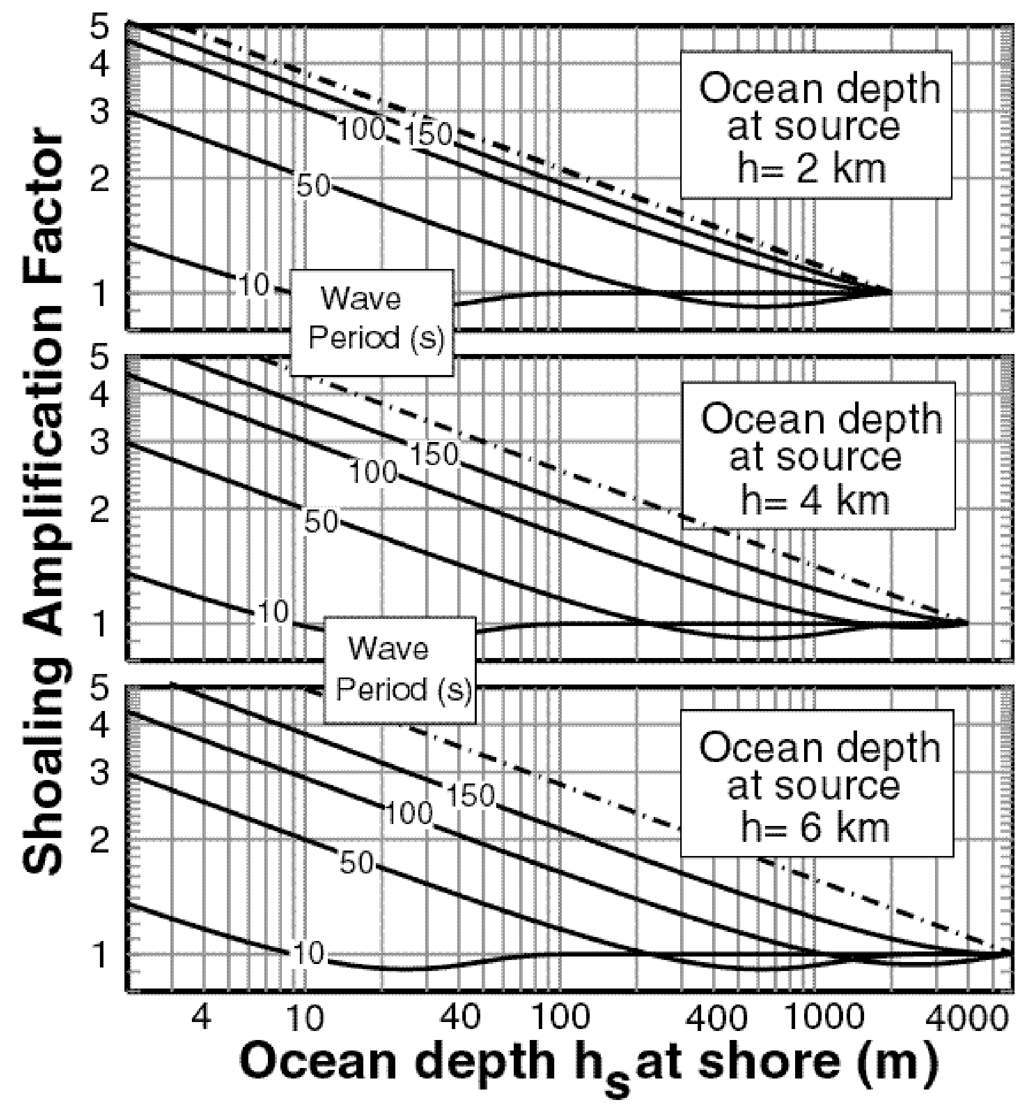
Tsunami Hazard Assessment

How does one infer the likelihood of a tsunami of a certain amplitude, striking a certain location within a certain time interval?

- 1) $H(M,r)$

2) $H_{crit} = H(M_c,r)(h_s/H_{crit})^{1/4}$





PTHA

How does one infer the likelihood of a tsunami of a certain amplitude, striking a certain location within a certain time interval?

- 1) $H(M,r)$ 2) $H_{crit} = H(M_c,r)(h_s/H_{crit})^{1/4}$
- 3) $N(H_{crit},r,h_s) =$

$$\int_{M_c(r,H_c)}^{M_{max}} n(M)dM$$

4) $N(H_{crit},h_s) =$

$$\int_{r(h_s)} N(H_{crit},r,h_s)dA$$

5) Poissonian probability of one or more tsunami arriving at r_s and exceeding H_{crit} in time interval T

$$P(r_s,T,H_{crit}) = 1 - e^{-N(r_s,H_{crit})T}$$

Slides taken from Tsunamis, by S. Ward, in
"Encyclopedia of Physical Science and Technology" - Academic Press - 2002

Modern THA

Natural Hazards (2006) 37: 277–314
DOI 10.1007/s11069-005-4646-z

Probabilistic Analysis of Tsunami Hazards*

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U.S. Geological Survey, 345 Middlefield Rd., MS 999Menlo Park, CA, 94025, USA

Pageoph (2007) 164, 2-3

Tsunami assessment for Risk management at nuclear powerplants

Yanagisawa et al.

Scenario based tsunami hazard assessment

- Assess the potential threat posed by earthquake generated tsunamis on the coastlines.
- Compilation a database of potentially tsunamigenic earthquake faults, to be used as input in the definition of scenarios.
- Each Source Zone includes an active tectonic structure with a Maximum Credible Earthquake and a typical fault.
- Provide information of the expected tsunami impact (e.g. height and arrival times) onto the target coastline; it can be progressively updated as knowledge of earthquake source advances.

Worst Credible Tsunami Scenario approach

- Identification of credible sources capable of producing the most significant tsunamis in the target area
- Simulation the propagation of the associated tsunamis and computation of the inundation in the target area
- Build of a unique aggregated scenario by combining together all of the computed scenarios: selection of the maximum value of a given physical variable (e.g. height)
- Subjectivity and the related uncertainties can be treated in this paper by performing a sensitivity analysis

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.

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

Deepest breakwater in Kamaishi (Iwate)

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.

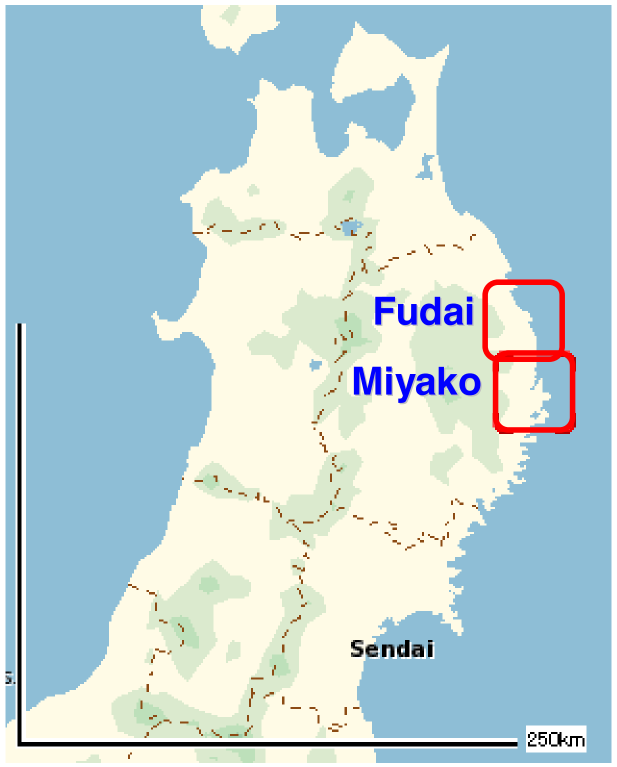
Woody Epstein, 2011

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…



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.

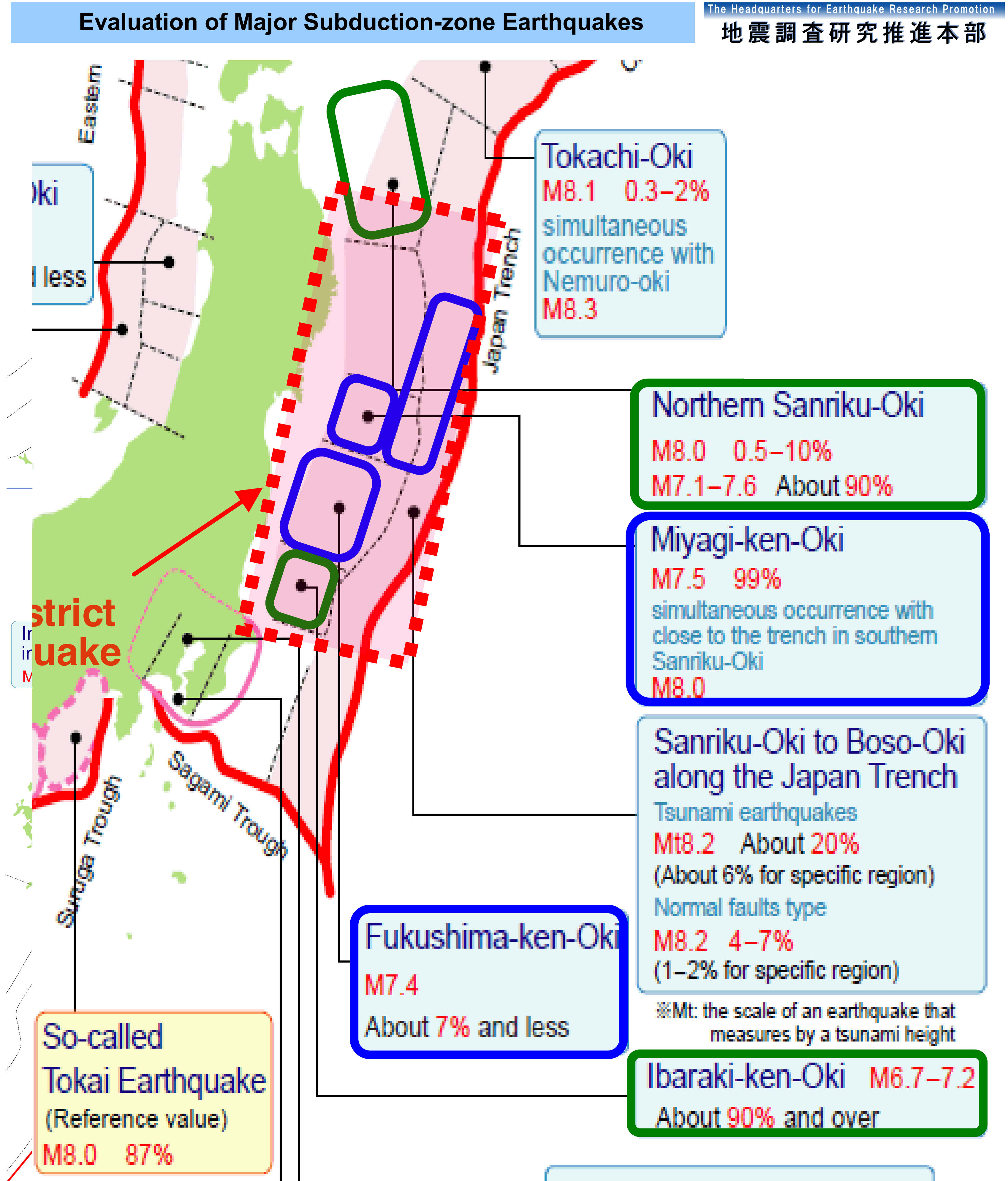
Fig. III-1-16 Difference of seawall heights resulting in different consequence.

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

Tsunami stones (Tsunami-seki)

Expectations...

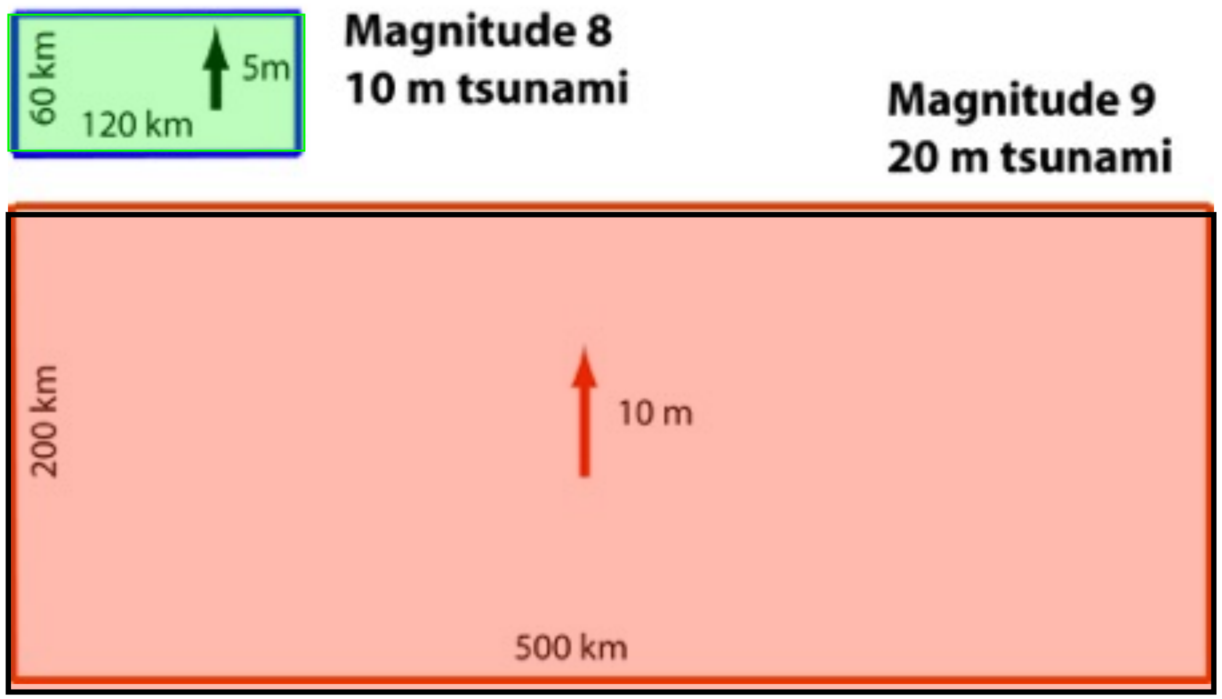


"Estimated magnitude and long-term possibilities within 30 years of earthquakes on regions of offshore based on Jan. 1, 2011."

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

Reality...

Planning assumed maximum magnitude 8 Seawalls 5-10 m high



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.