Emerging techniques and technologies for faster and more accurate tsunami forecasts

Kenji Satake
University of Tokyo

New methods for tsunami warning
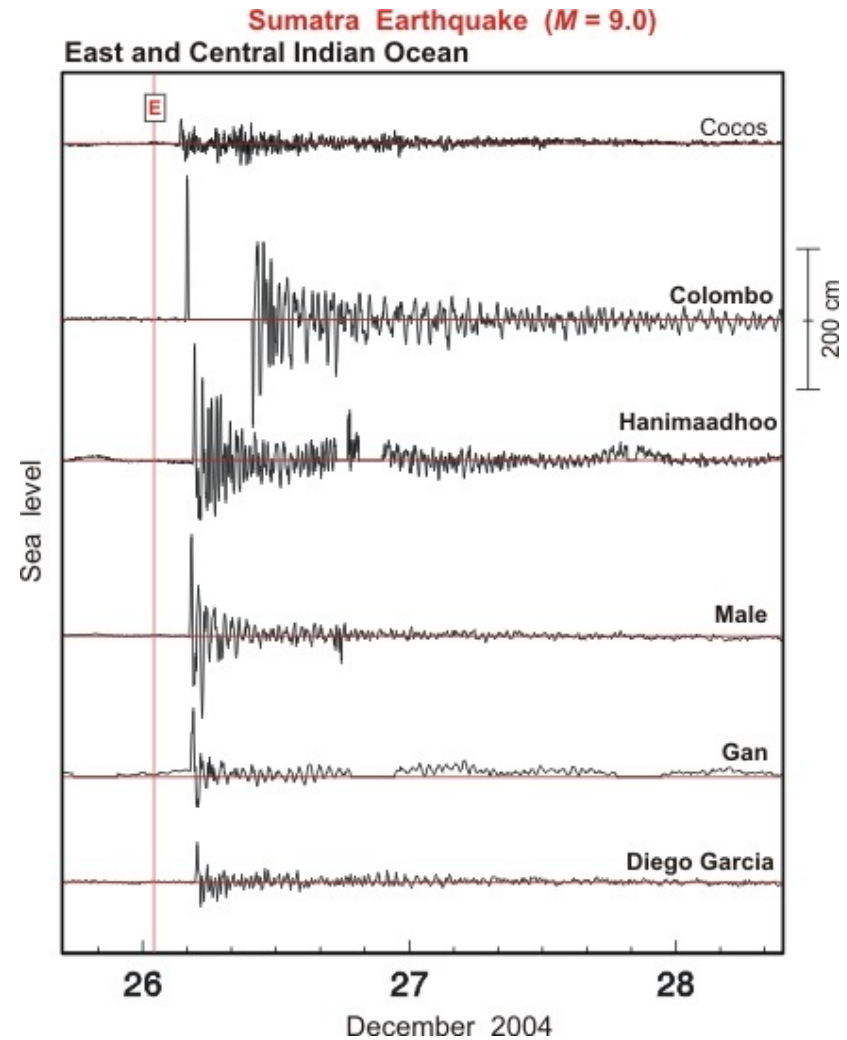
- **New types of tsunami observations**

- **Estimation of tsunami source**

  - ☐ From sea level data

  - ☐ From GPS(GNSS) data

  - ☐ From ionospheric data

- **Data assimilation**

  - ☐ Bottom pressure data

  - ☐ Radar data

- **Atmospheric pressure waves**

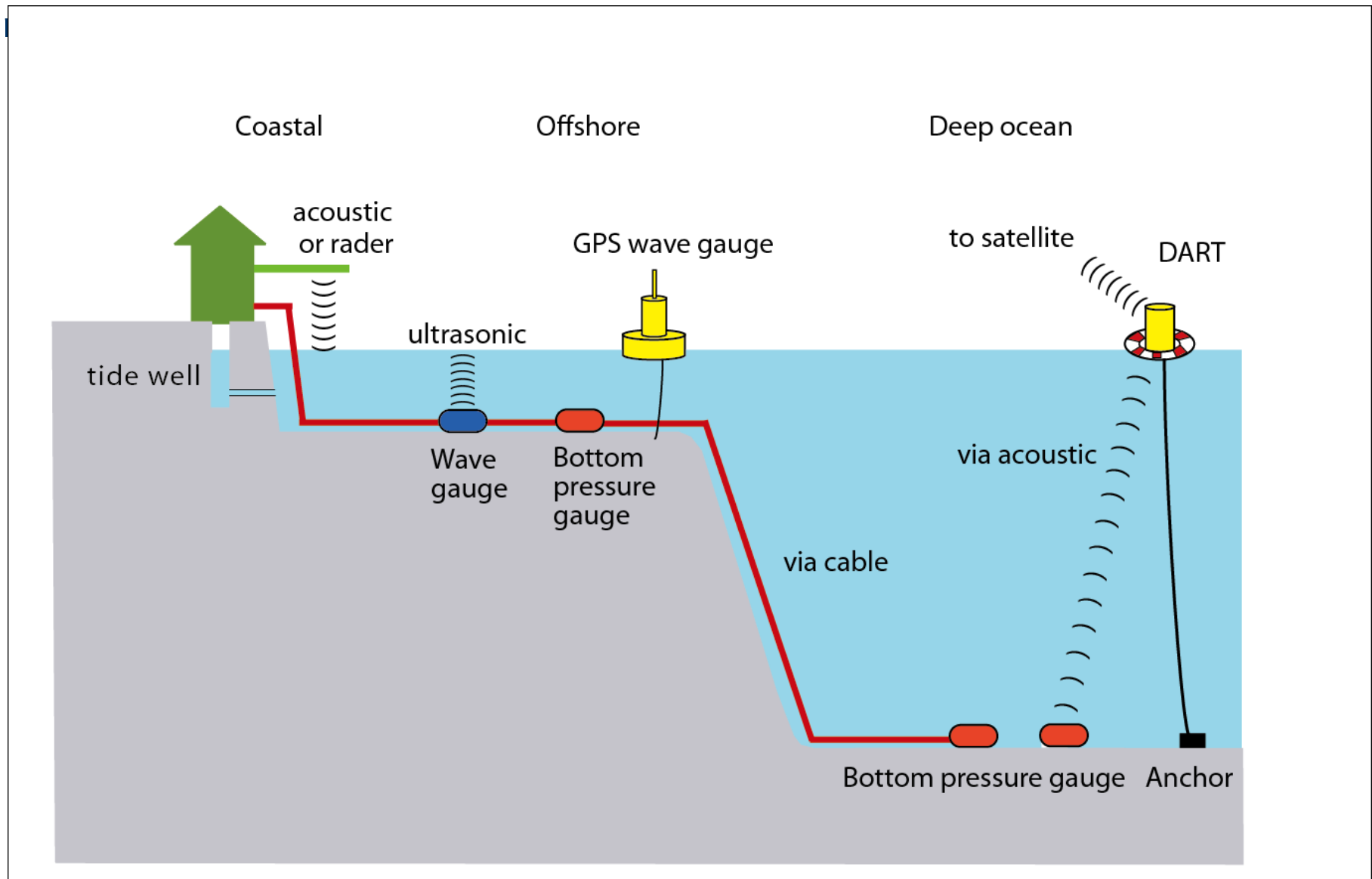# Coastal Tide Gauges

Acoustic gauge

Float gauge

Sumatra Earthquake (M = 9.0)
East and Central Indian Ocean

http://www-sci.pac.dfo-mpo.gc.ca/osap/projects/tsunami/tsunamiasia_e.htm

Tsunami Observation Systems

Coastal | Offshore | Deep ocean

acoustic or rader · GPS wave gauge · to satellite · DART

tide well · ultrasonic · Wave gauge · Bottom pressure gauge · via acoustic · via cable · Bottom pressure gauge · Anchor
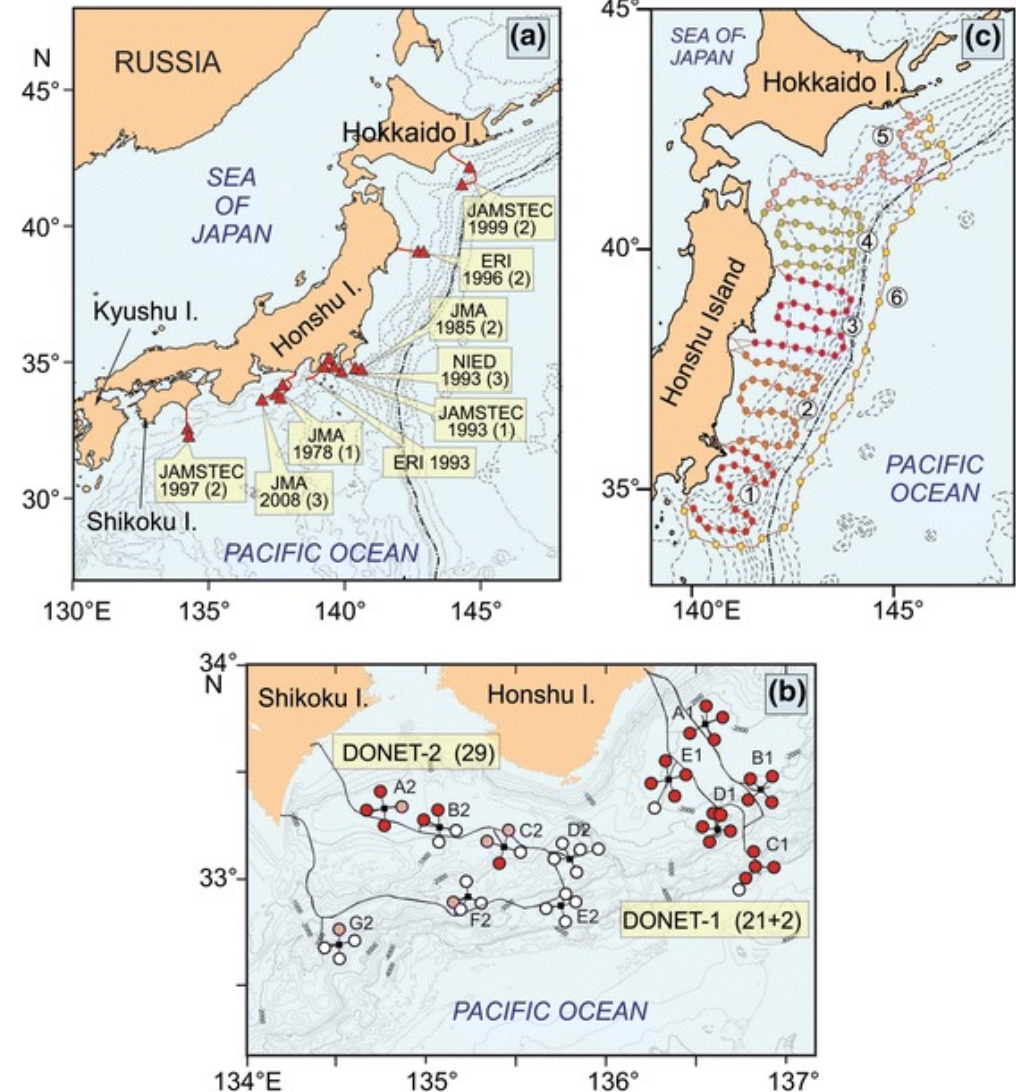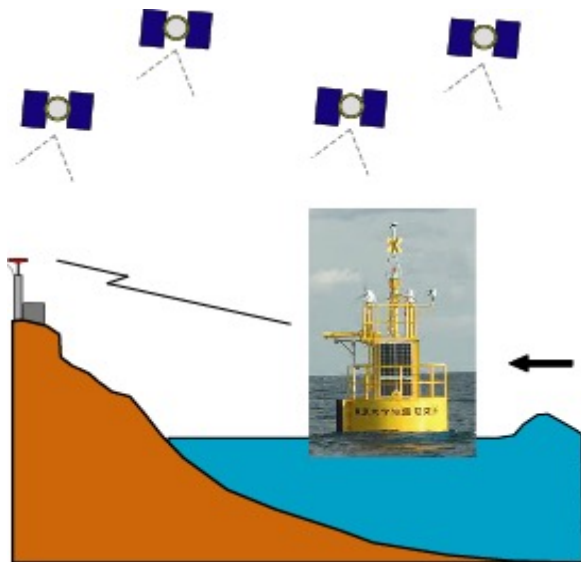
Satake (2014, Geosci. Lett.)

Tsunami Observation Systems

Bottom Pressure Gauges on submarine cables
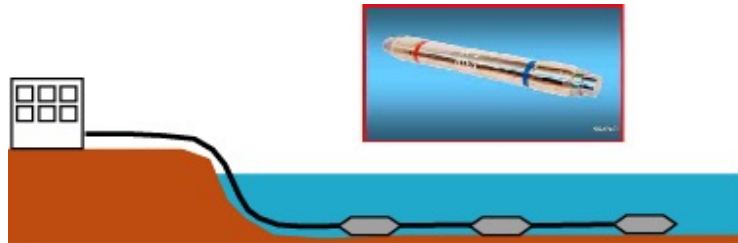
GPS tsunami gauge

Rabinovich and Eble (2015, Pageoph)

DART buoys (NOAA)

Satellite Altimetry Data

2004 Sumatra Earthquake   00 hr 01 min
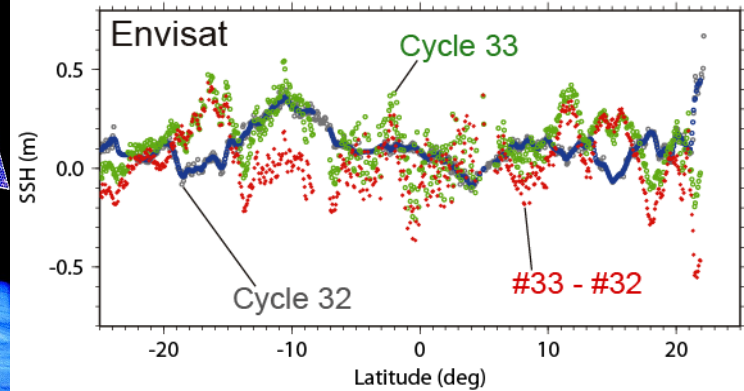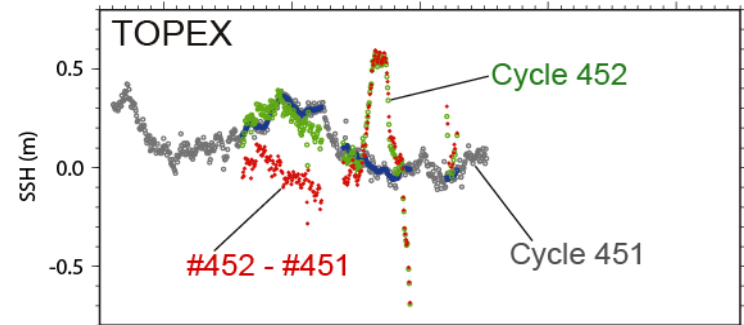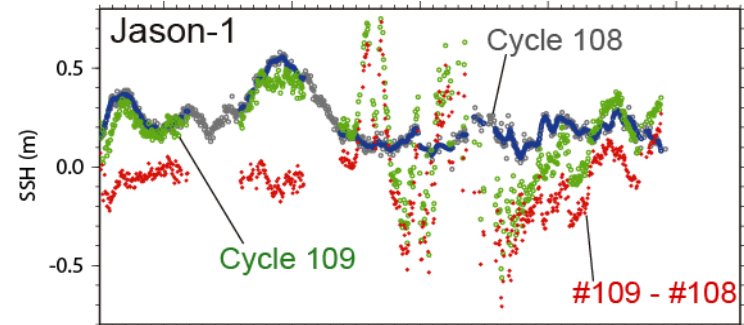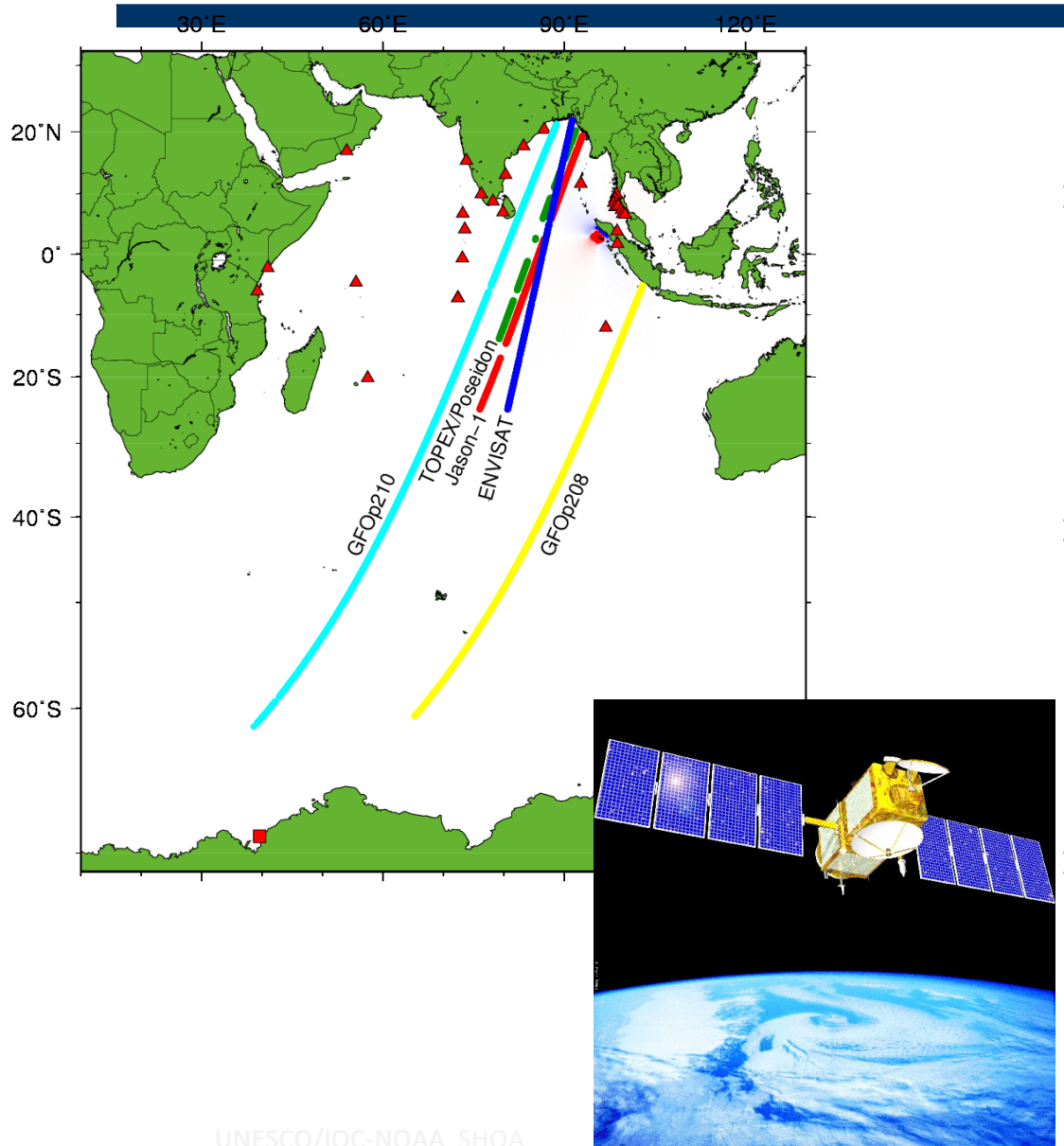
Coastal HF (high-frequency) radar
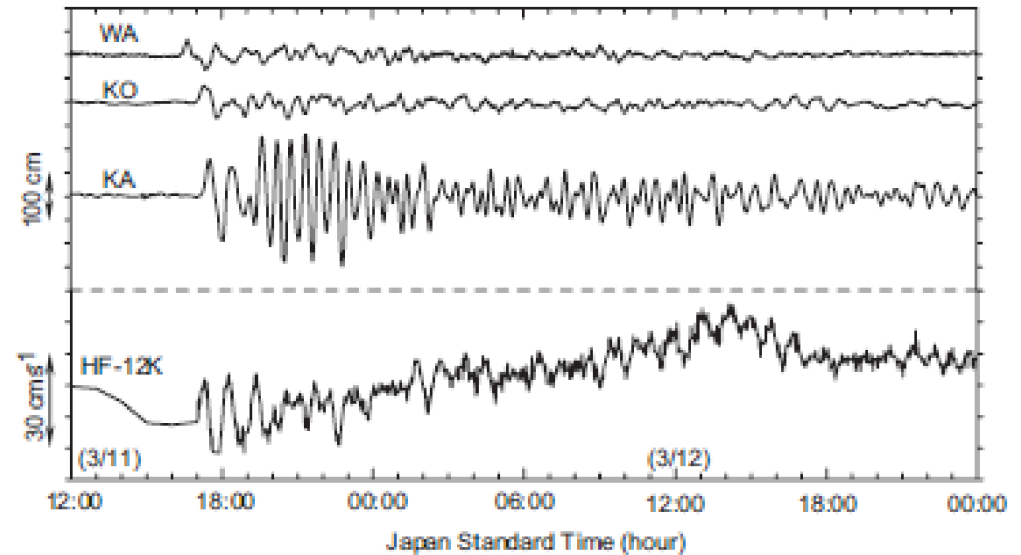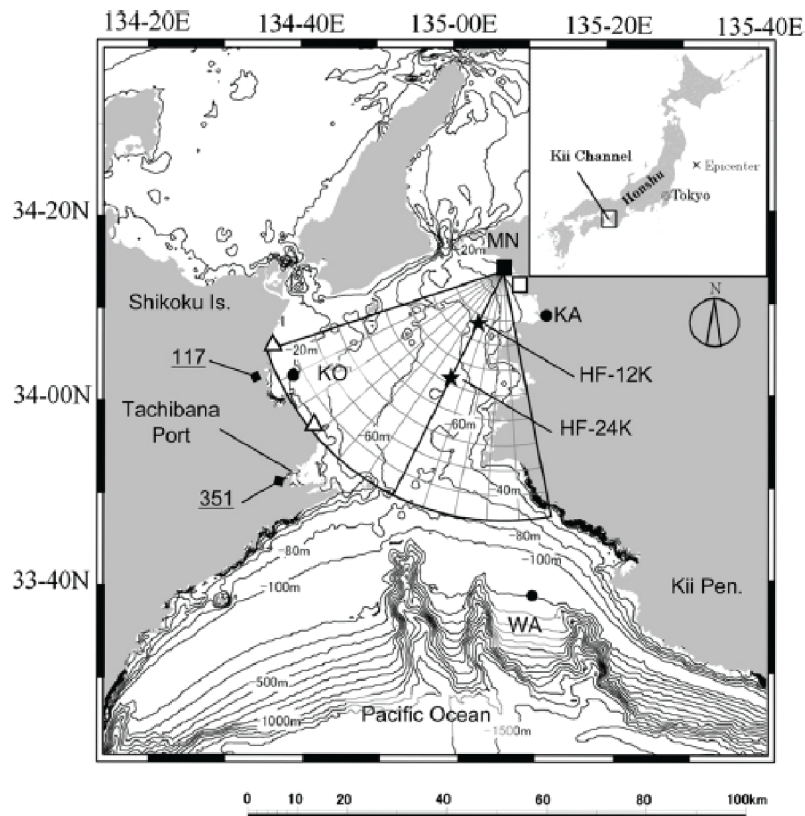
square and triangles: HF (24.5 MHz) ocean surface radar systems
WA: GPS buoy
KO: offshore wave gauge
KA: coastal tide gauge
HF-12K: radial velocity at 12 km offshore from the radar.

Hinata et al. (2011)

Ionospheric disturbances
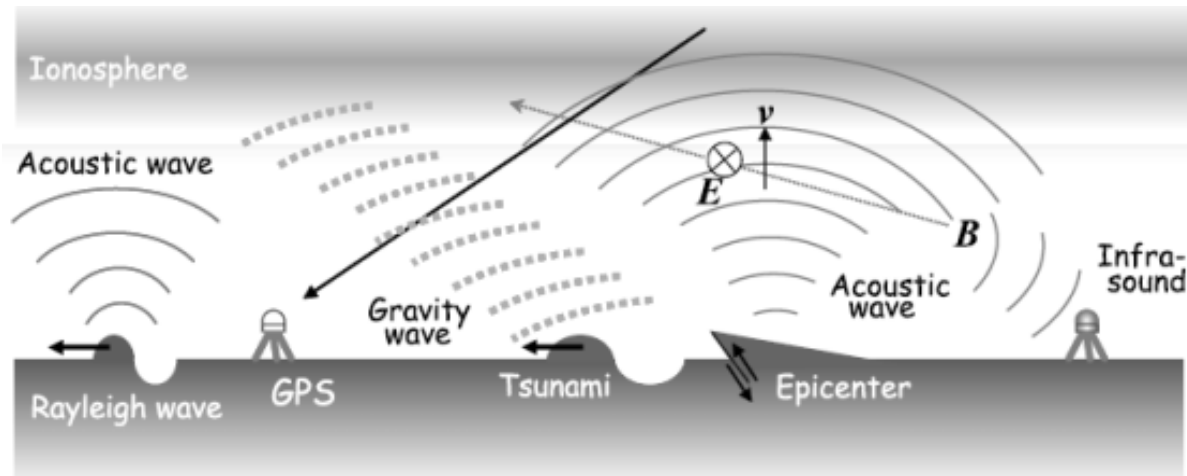
Heki et al. (2006)

(1) direct acoustic wave from the focal area
(2) gravity wave propagating obliquely upward from the focal area or from propagating tsunami
(3) secondary acoustic wave excited in far fields by the Rayleigh surface wave.

2004 Sumatra-Andaman
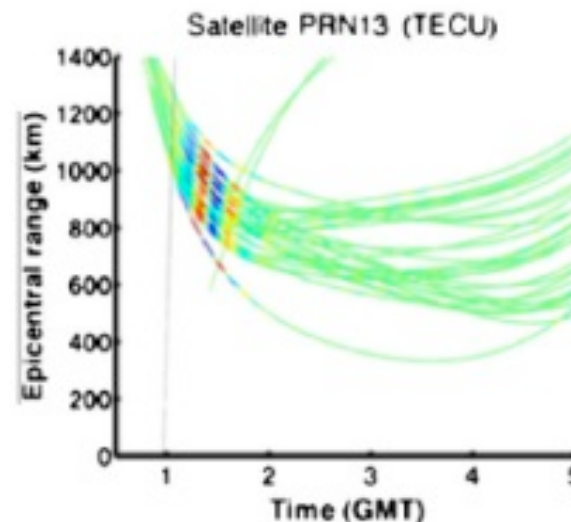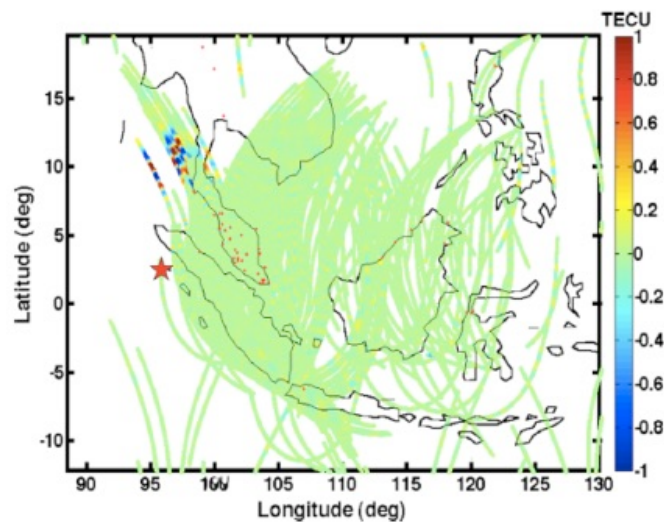
TEC
Total Electron Content

Occhipinti et al. (2013)
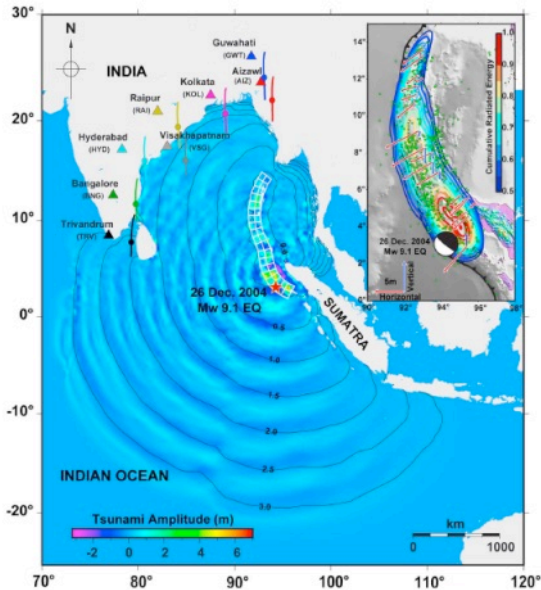
Ionospheric disturbances
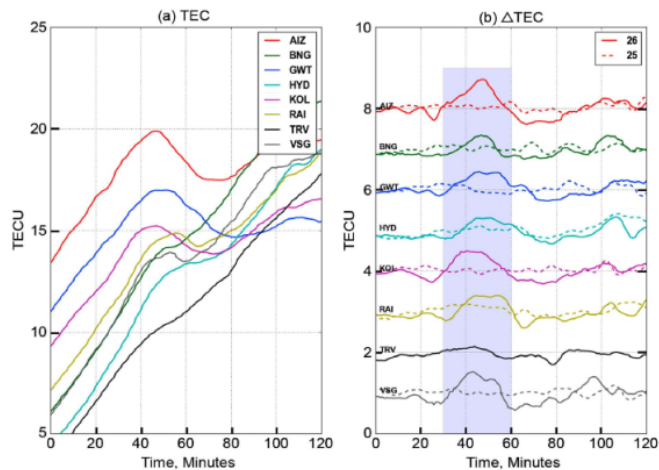
Simulation

Bagiya et al. (2017)

Observed TEC anomalies
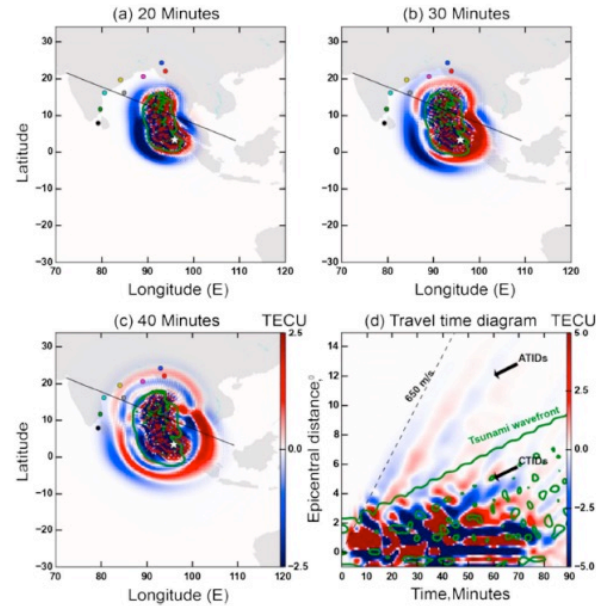
Tsunami size and TEC anomaly
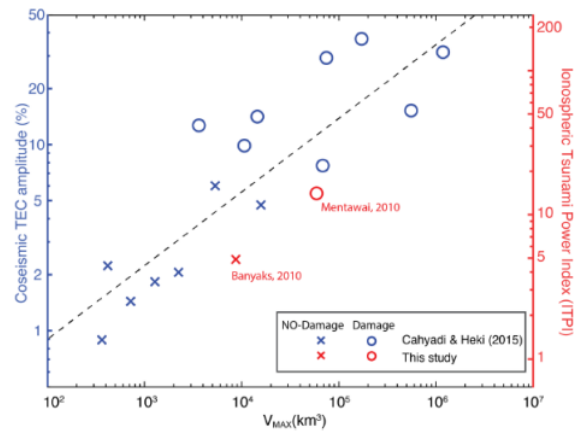
Manta et al. (2020)

Tsunami and GNSS observation systems
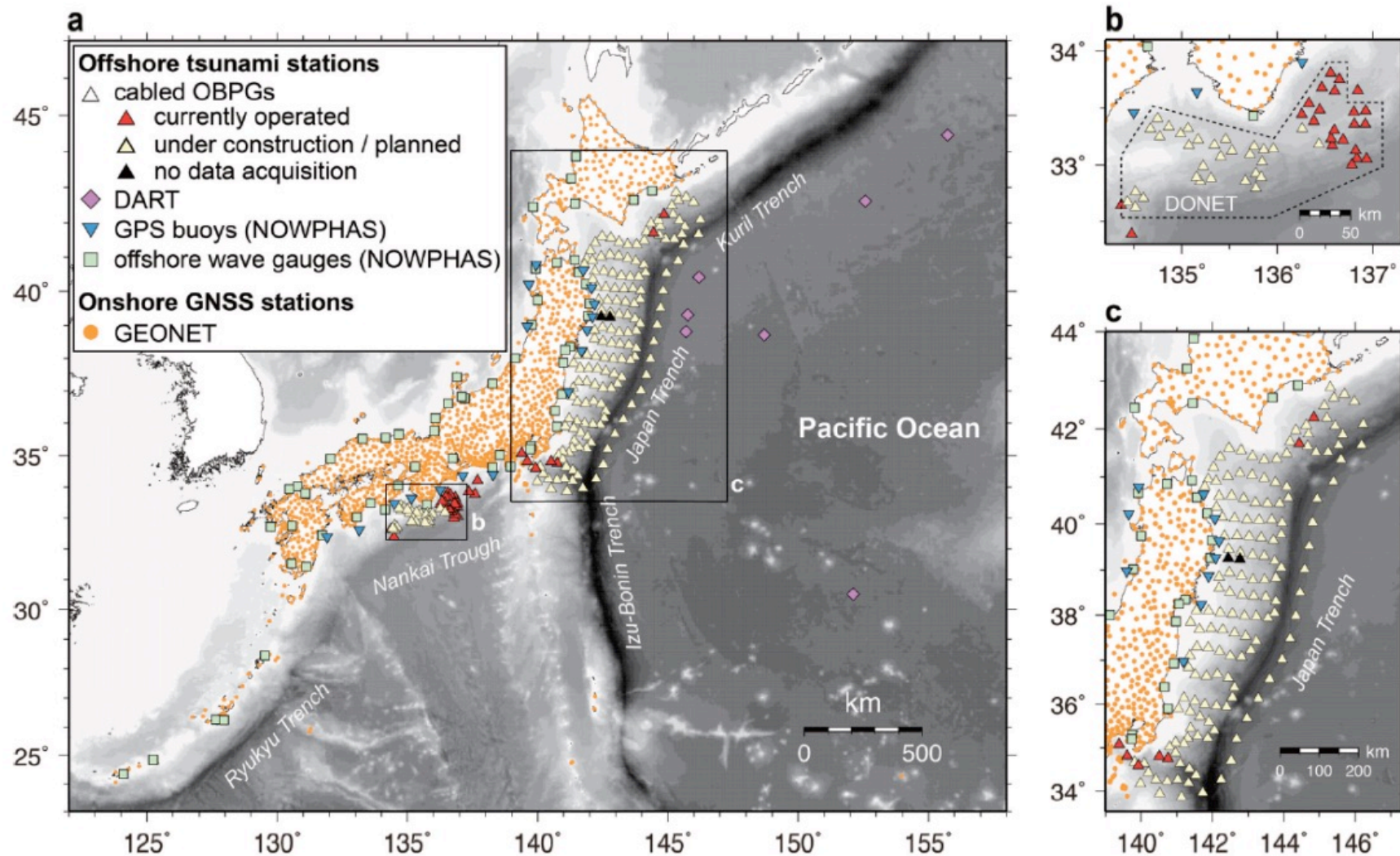
Tsushima and Ohta (2014)
https://doi.org/10.20965/jdr.2014.p0339

REGARD(the Real-time GEONET Analysis system for Rapid Deformation monitoring)

Kawamoto et al. 2017
https://doi.org/10.1002/2016JB013485
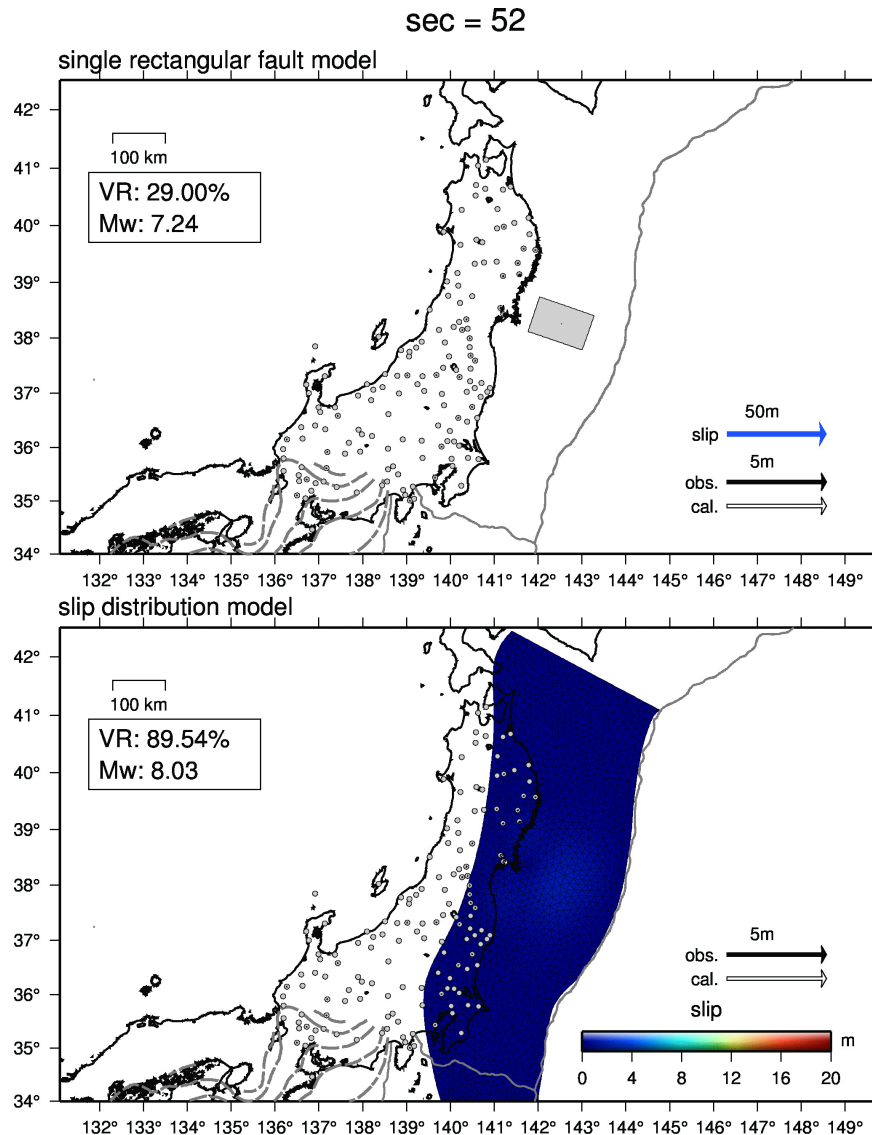
REGARD(the Real-time GEONET Analysis system for Rapid Deformation monitoring)
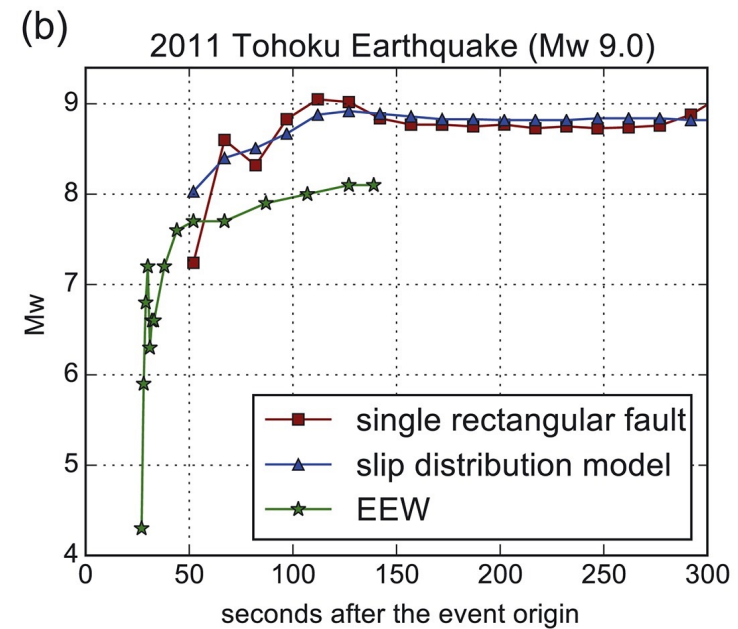
Kawamoto et al. 2017
https://doi.org/10.1002/2016JB013485
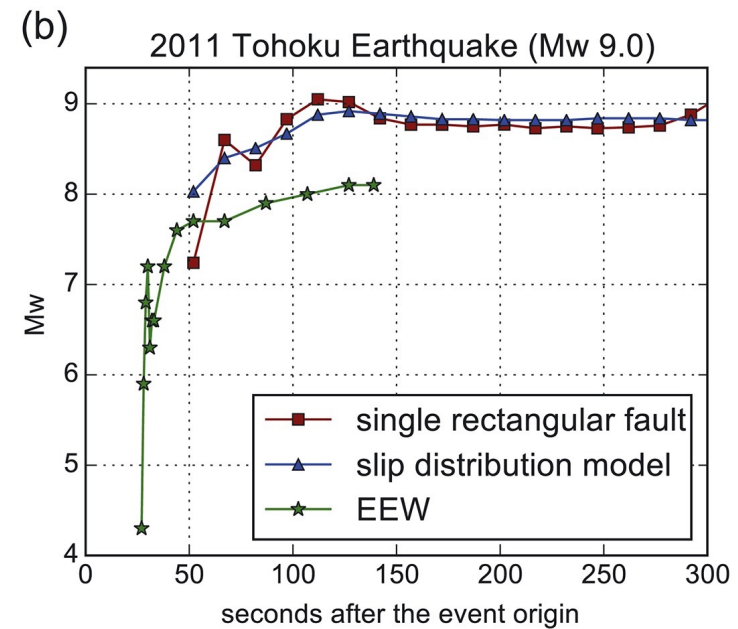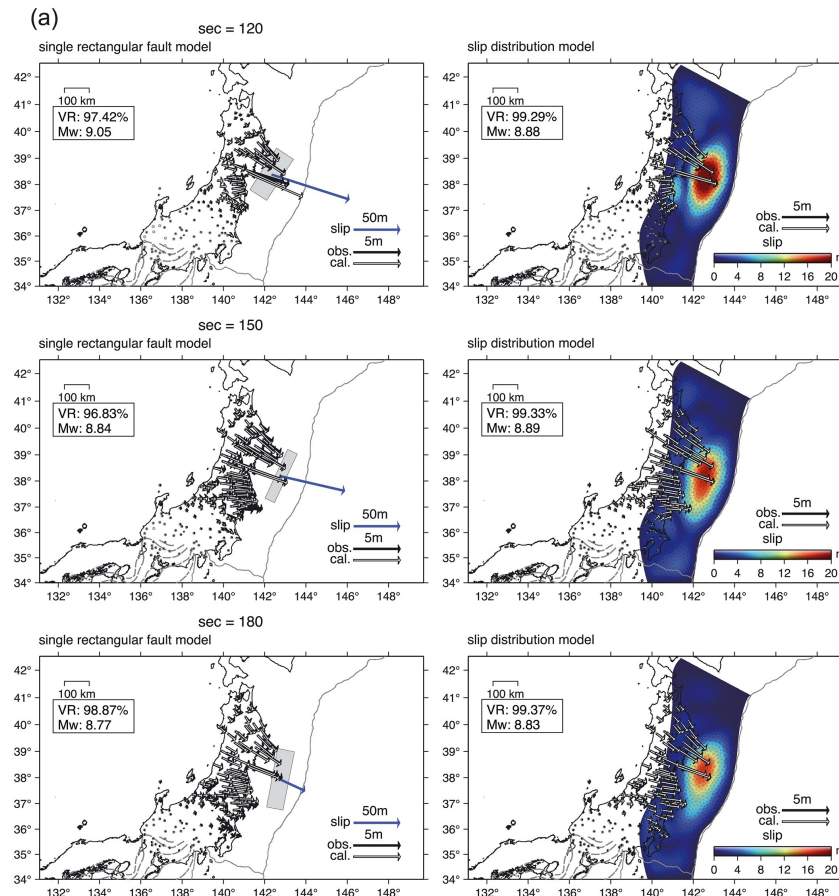
Real-time Inversion or Data Assimilation

generation

geological processes
earthquakes
volcanic eruptions
landslides

propagation

computer simulation

coastal behaviors

water height
current
damage
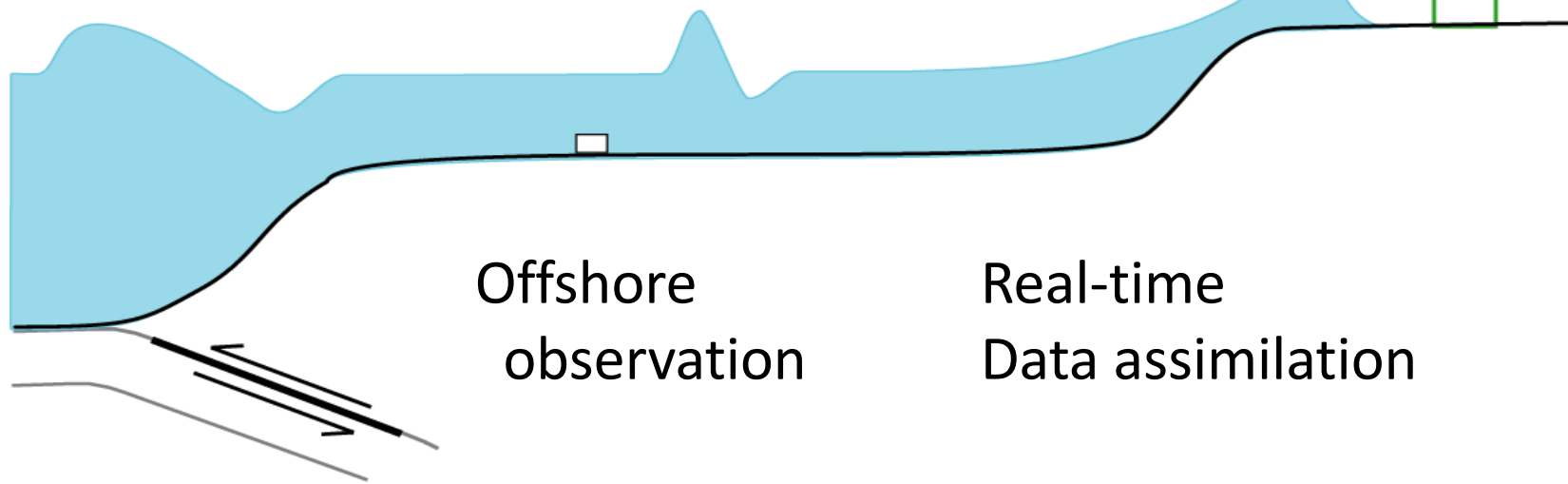
Offshore
observation

Real-time
Data assimilation

Seismic
detection,
modeling

→

Tsunami
data

→

Tsunami
forecast,
warning

DART Data Assimilation by US NOAA

Japan (Tohoku) tsunami, March 11, 2011
Maximum wave amplitudes
NOAA Center for Tsunami Research
NOAA Research Product, not an official forecast
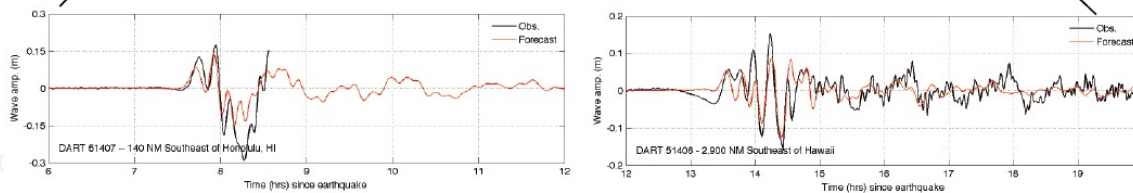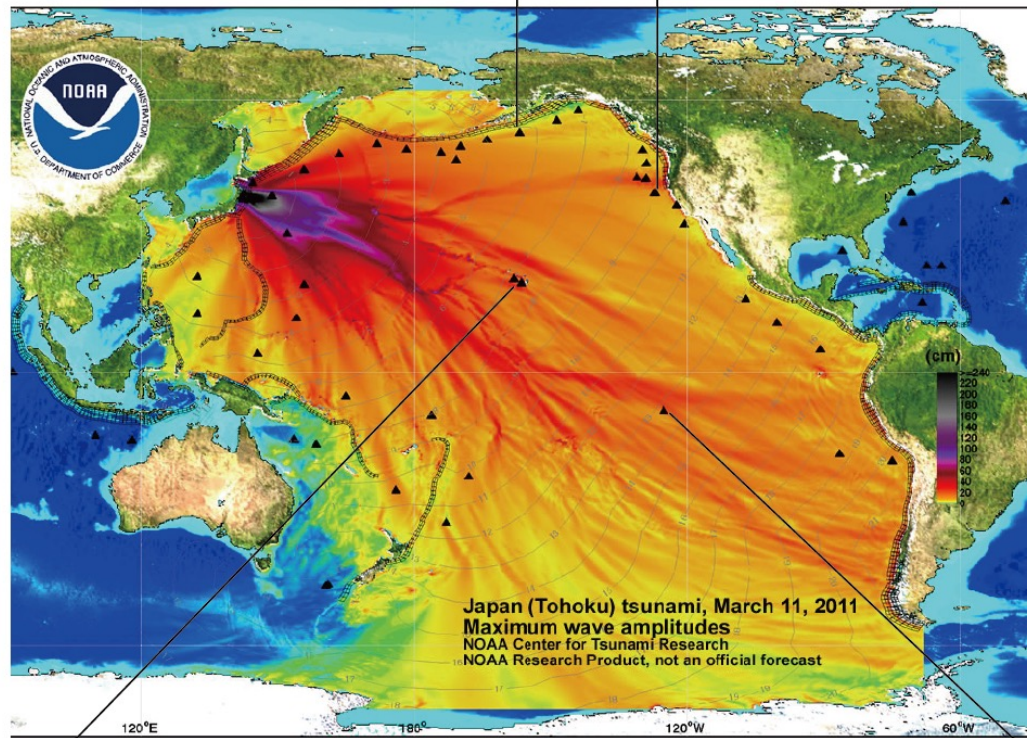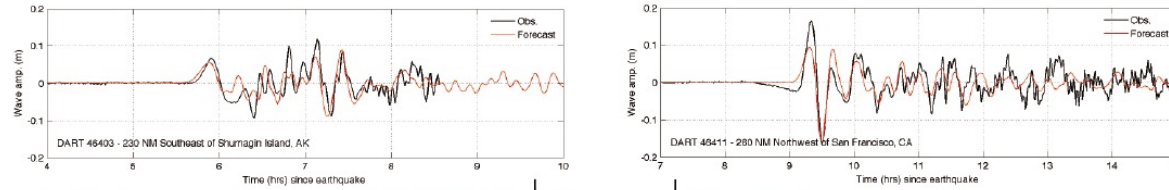
Source inversion and data assimilation
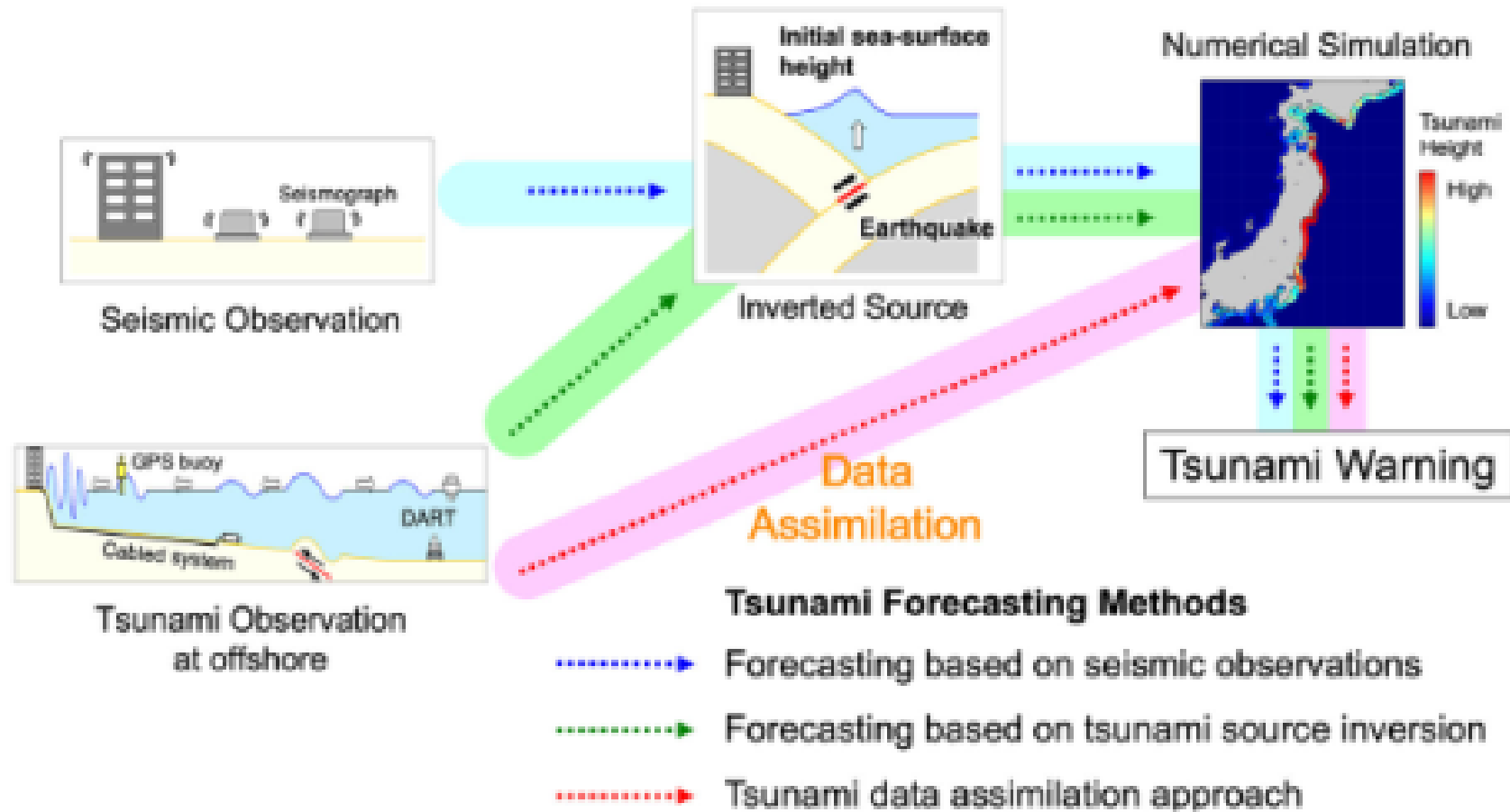
Wang et al. (2021)
https://doi.org/10.1007/s00024-021-02910-z

tFISH: tsunami Forecasting based on Inversion for initial sea-Surface Height

10 min after the earthquake occurrence

Synthetic wavefield

Forecasting without S-net (11 March 2011)

tFISH: tsunami Forecasting based on Inversion for initial sea-Surface Height

10 min after the earthquake occurrence

Forecasting with S-net (Present)

▽ : Offshore station on 11 March 2011
▽ : S-net station
■ : Point near coast

Tsunami early warning using data assimilation

Seismic Observation   Source estimation   Numerical Simulation
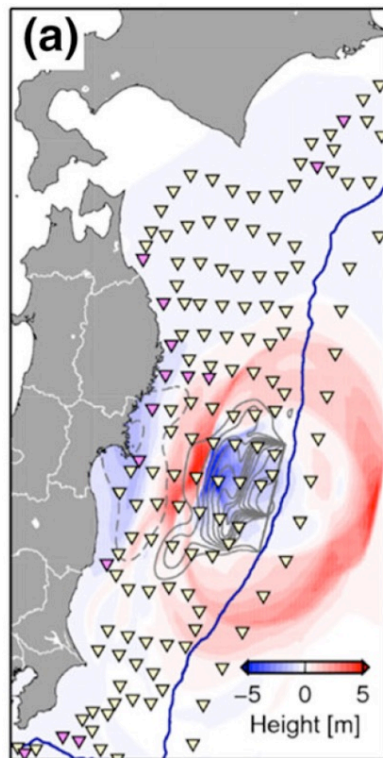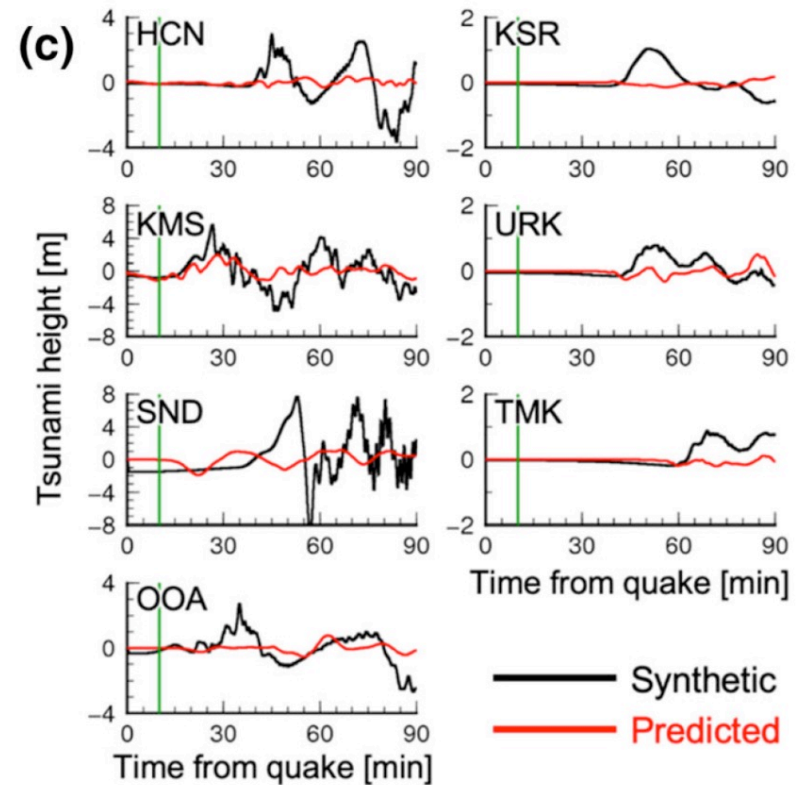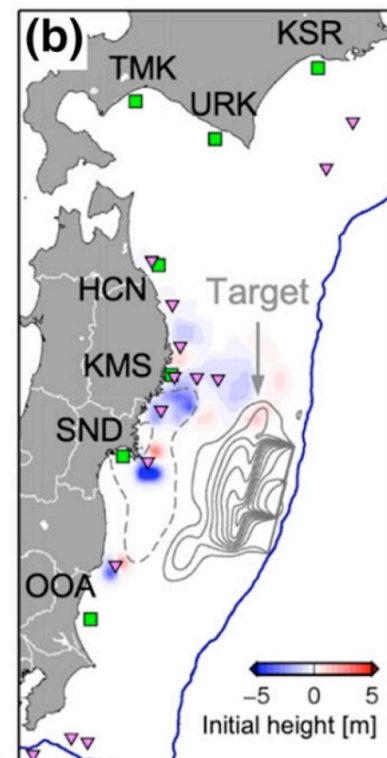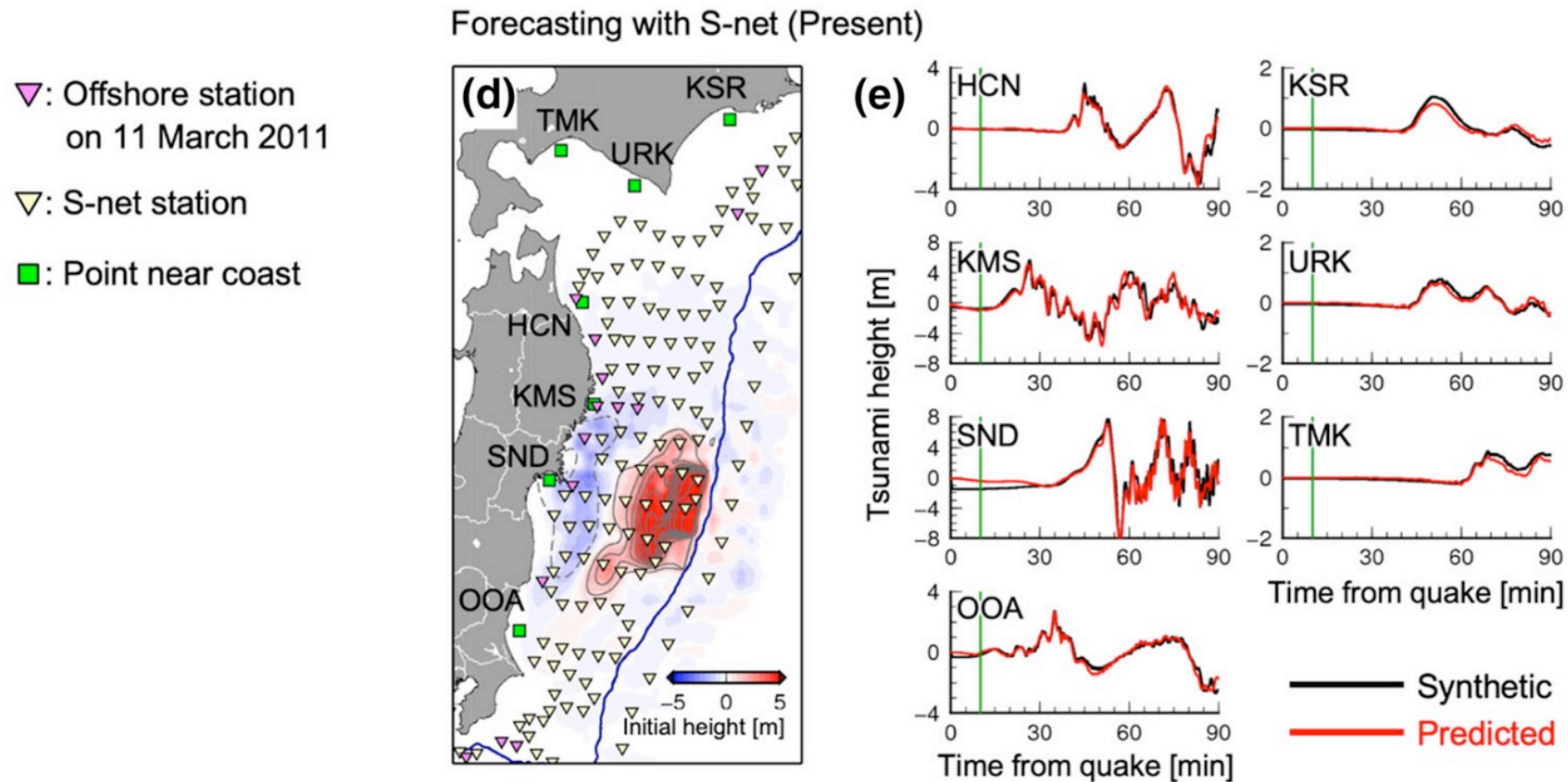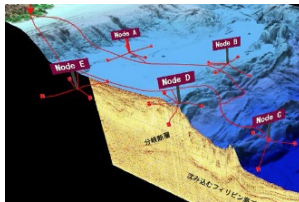

Offshore Tsunami Observation

Large tsunami warning
Tsunami warning
Watch

Data Assimilation

Tsunami Warning

06:00 UTC, 8 October 2019   TY 1919

06 UTC, 13 Oct.
06 UTC, 12 Oct.
06 UTC, 11 Oct.
06 UTC, 10 Oct.
06 UTC, 9 Oct.
18 UTC, 8 Oct.

≥ 50 kt wind area
≥ 30 kt wind area
Storm warning area
70% probability circle of center position forecast

All rights reserved. Copyright © Japan Meteorological Agency
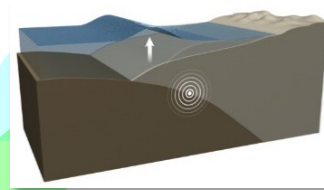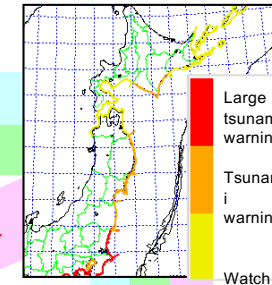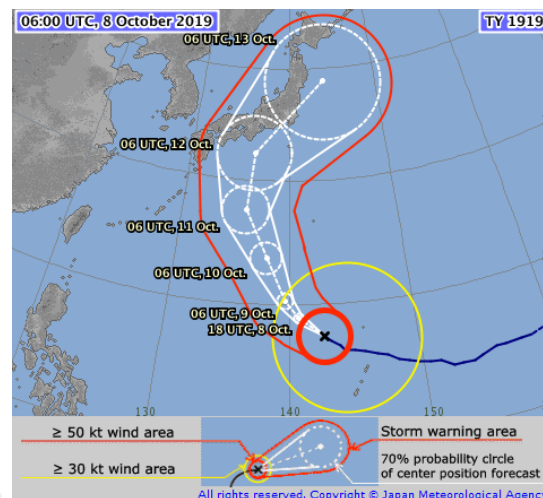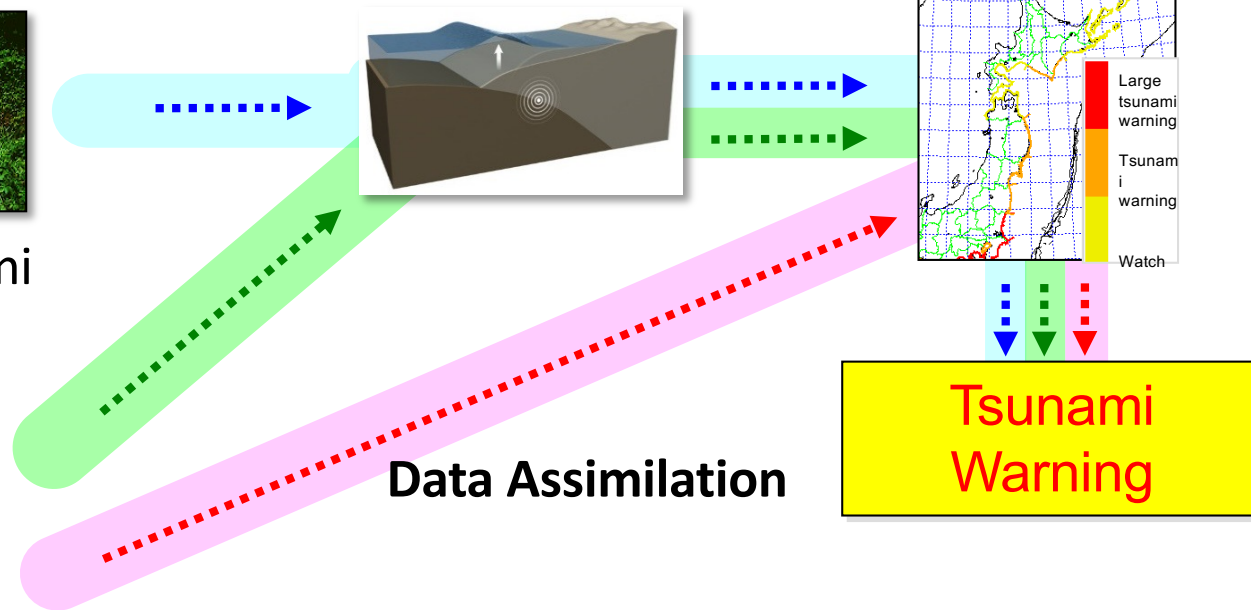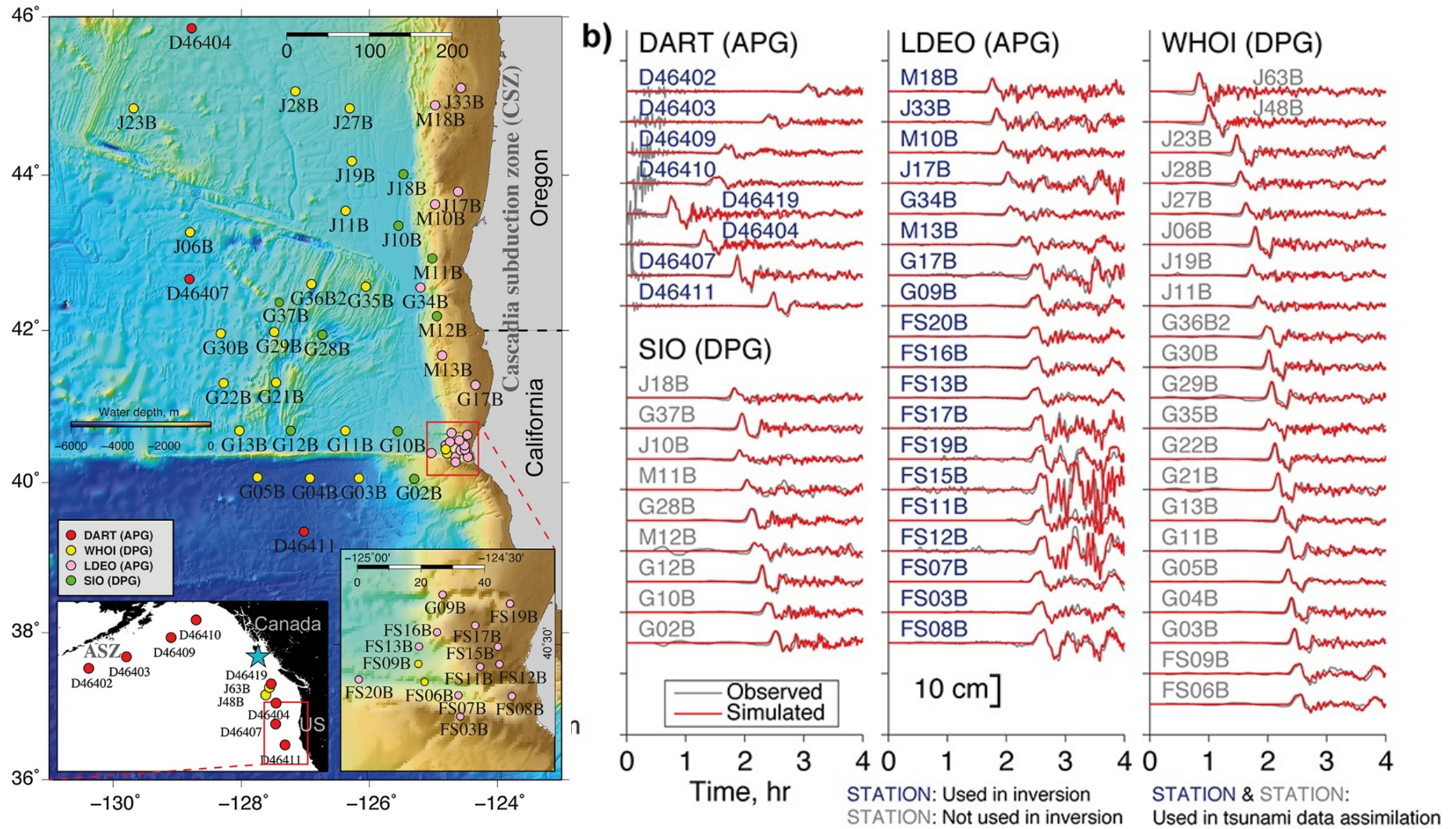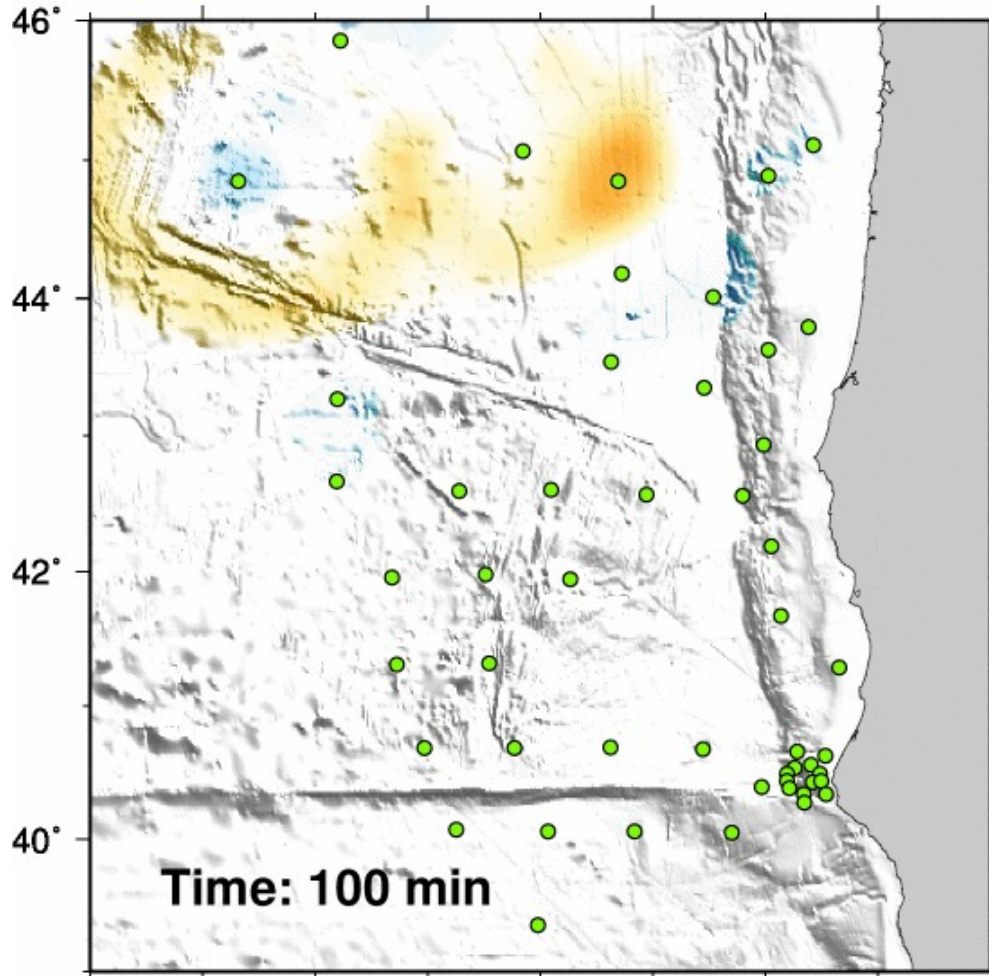
Data Assimilation in Meteorology

Forecasting typhoon movement
- No source information
- Current status
- Numerical simulation

Cascadia array recorded tsunamis from the 2012 Haida Gwaii earthquake

Gusman et al. (2016, GRL)
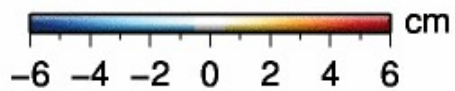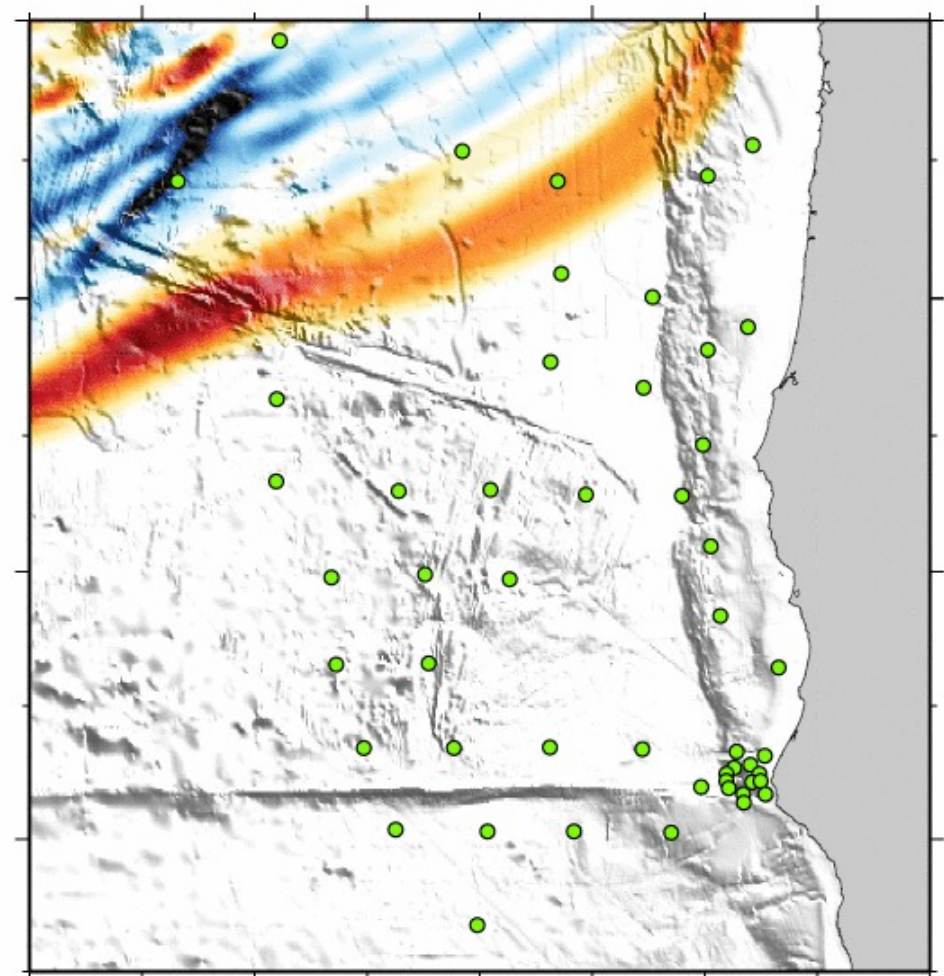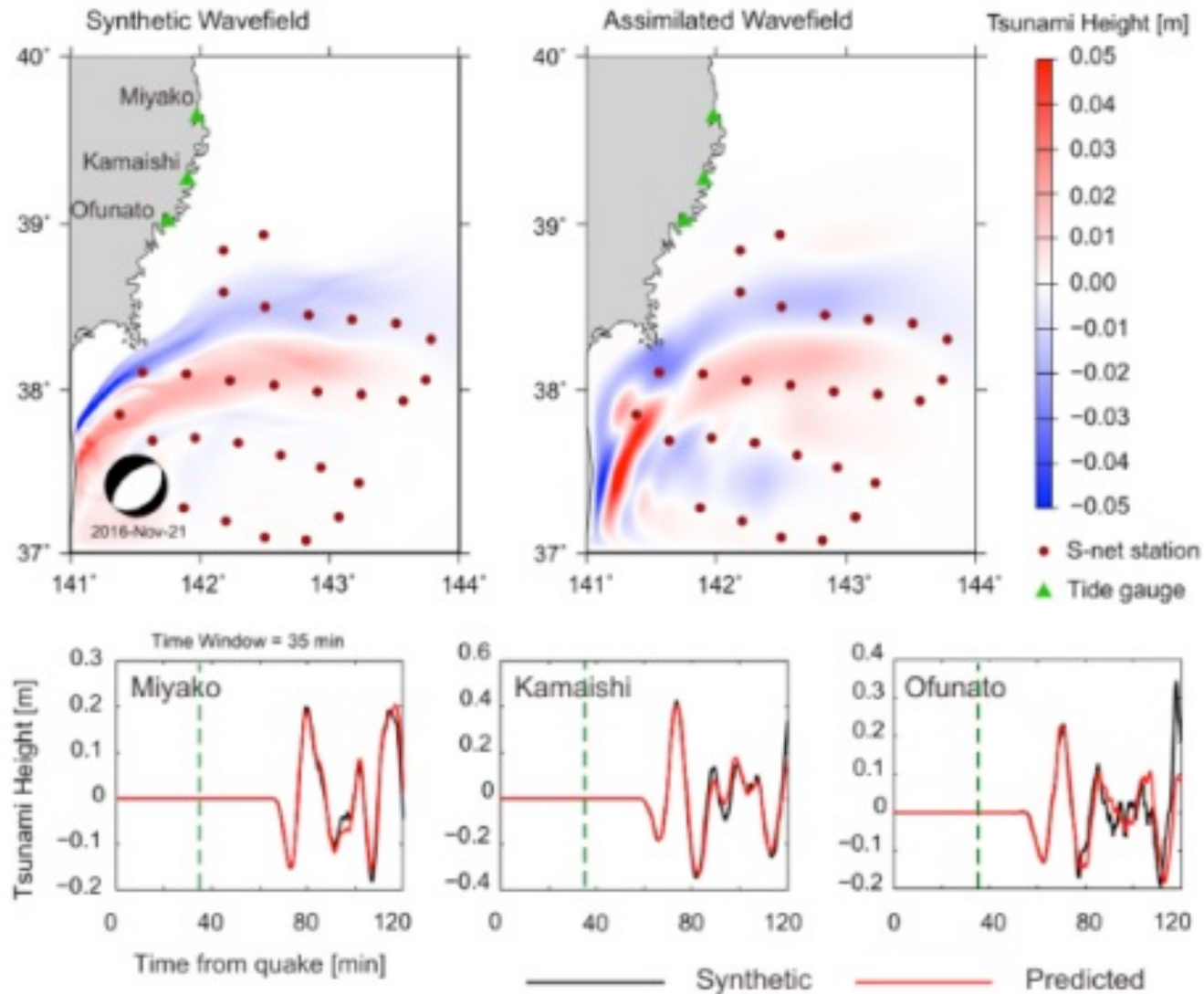
Data Assimilation

Gusman et al. (2016, GRL)

Data Assimilation

Wang et al. (2021)
https://doi.org/10.1007/s00024-021-02910-z

Data assimilation of S-net and HF radar data

Wang et al. (2022) https://doi.org/10.1029/2022JB025153
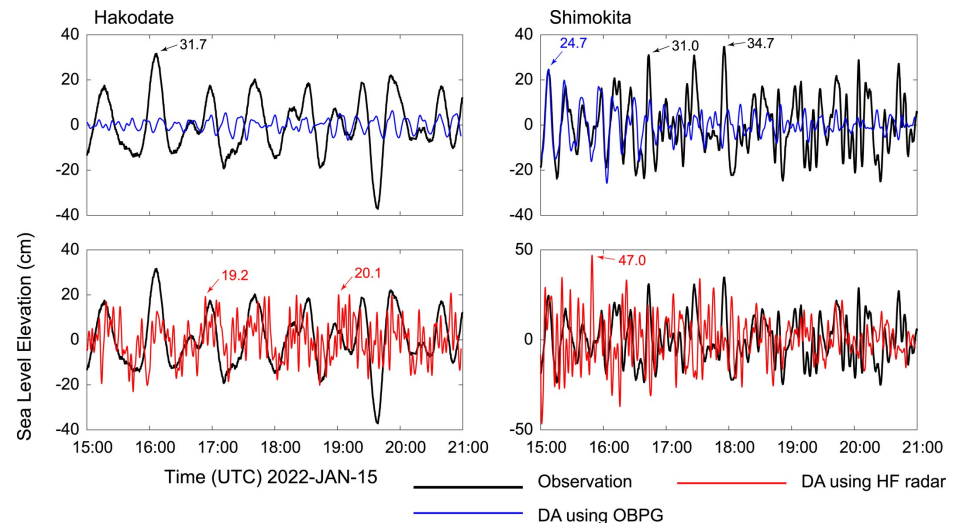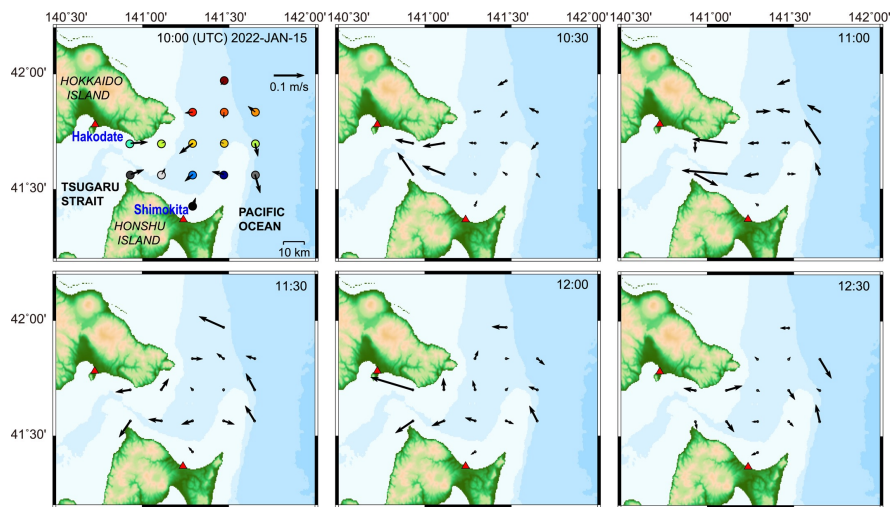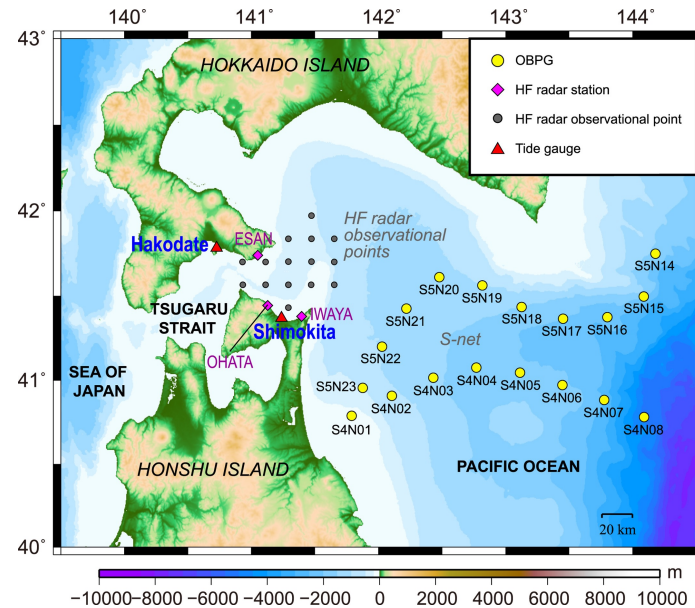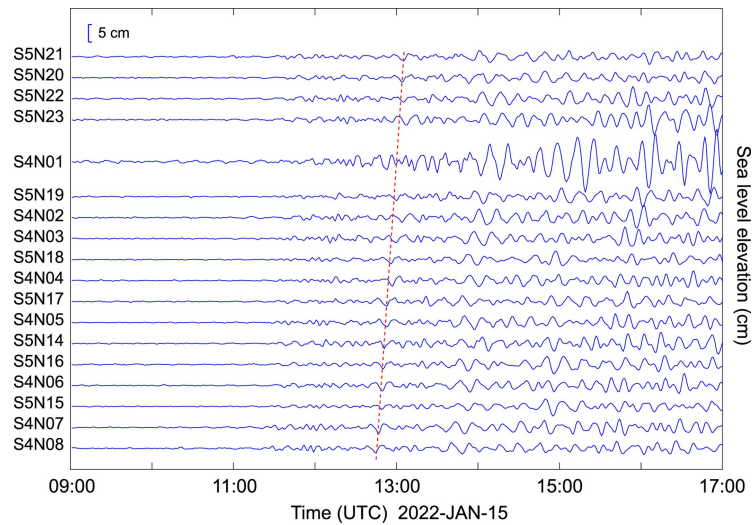
Hunga Tonga- Hunga Ha'apai eruption 2022

A big eruption occurred at around 4 UT on January 15, 2022.
The eruption column reached 16, 000 m
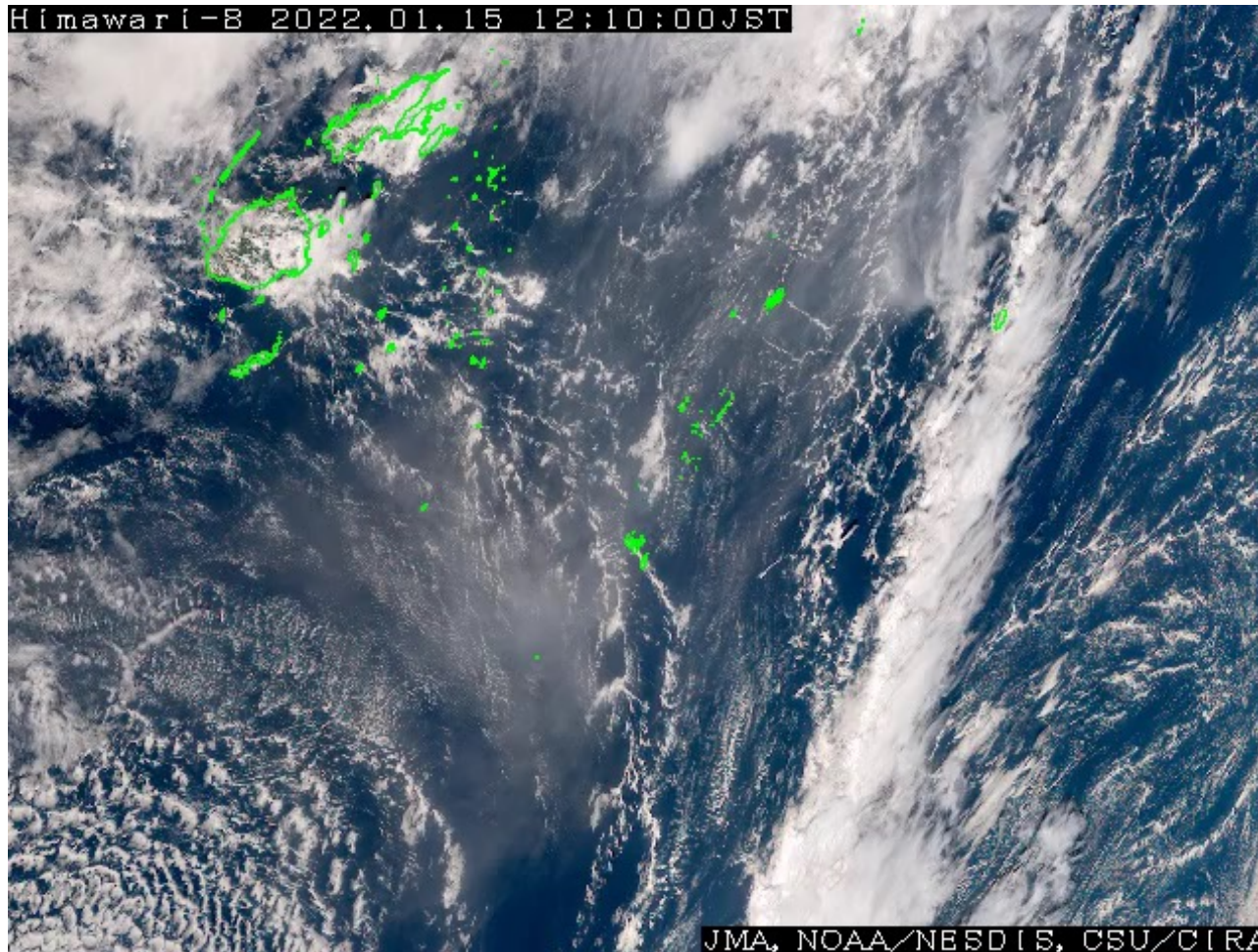
January 15, 2022 3 h to 12 UT
True color (day time) and infrared (night time)

Hunga Tonga- Hunga Ha'apai eruption 2022

Atmospheric pressure waves
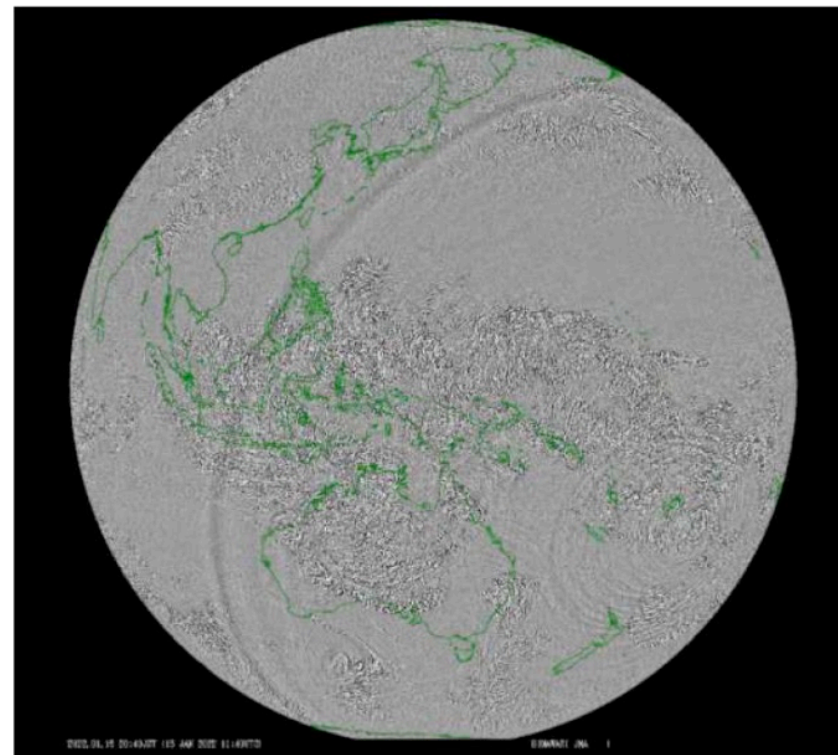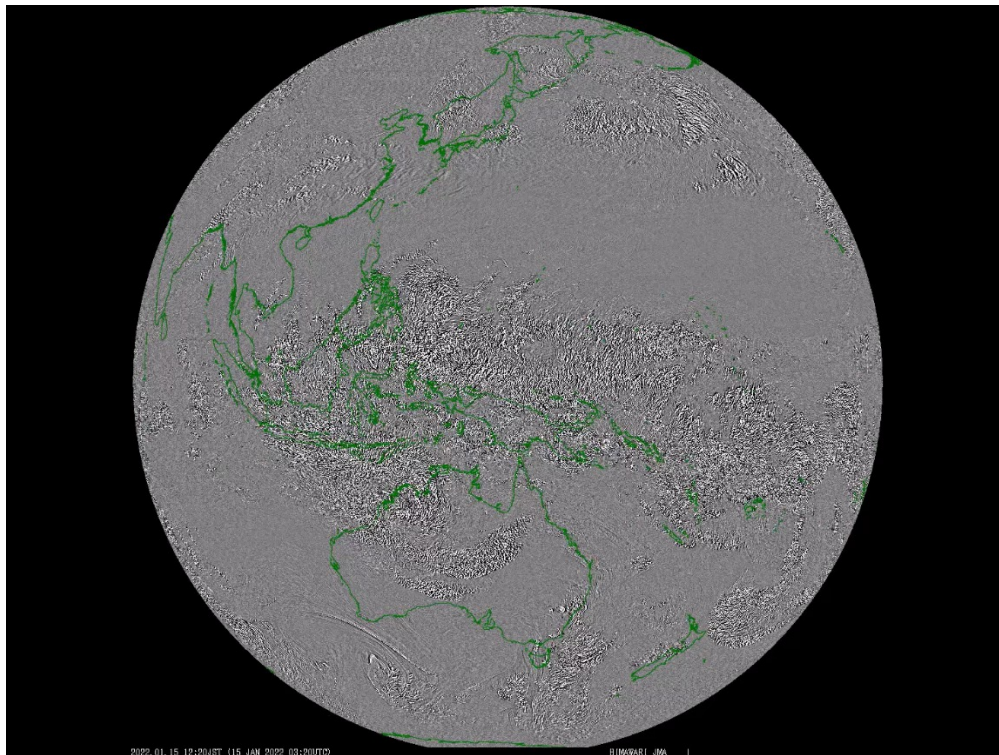
11:40 UT January 15

Hunga Tonga- Hunga Ha'apai eruption 2022

Tsunami toward Japan
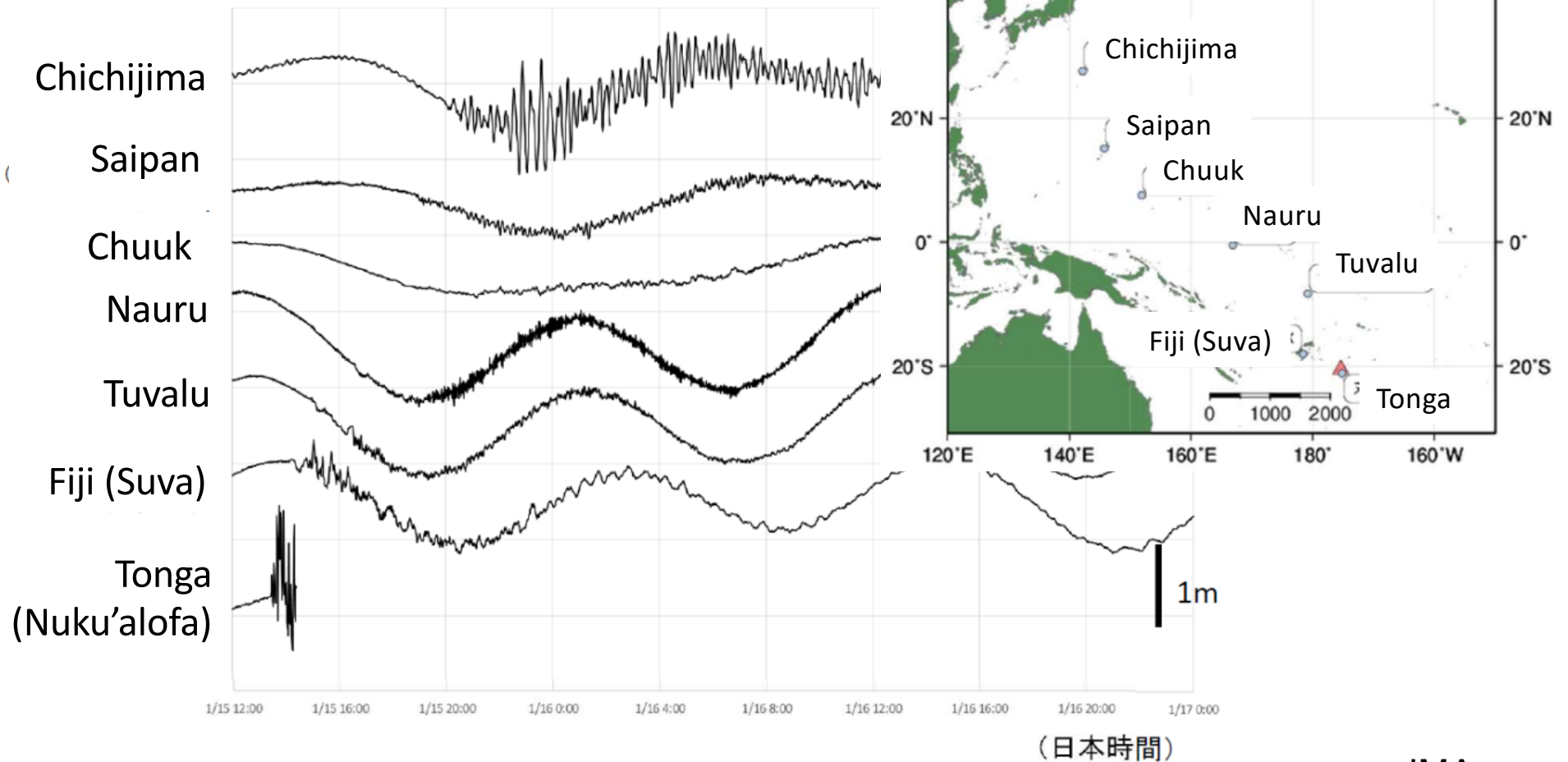
Hunga Tonga- Hunga Ha'apai eruption 2022

Air pressure and sea level in Japan

Chichijima

Amami

Sea level (cm)
(tidal change removed)

Atmospheric Pressure
(hPa)

Sea level

Atmospheric Pressure

9 UT   12 UT   15 UT   18 UT   21 UT

Hunga Tonga- Hunga Ha'apai eruption 2022

Gravity wave   Lamb wave

V_0 $\sim c_0$ Eruption $\sim c_0$ V_0

(1)   (2)   (2)   (1)

V_0 c_0 c_0 V_0
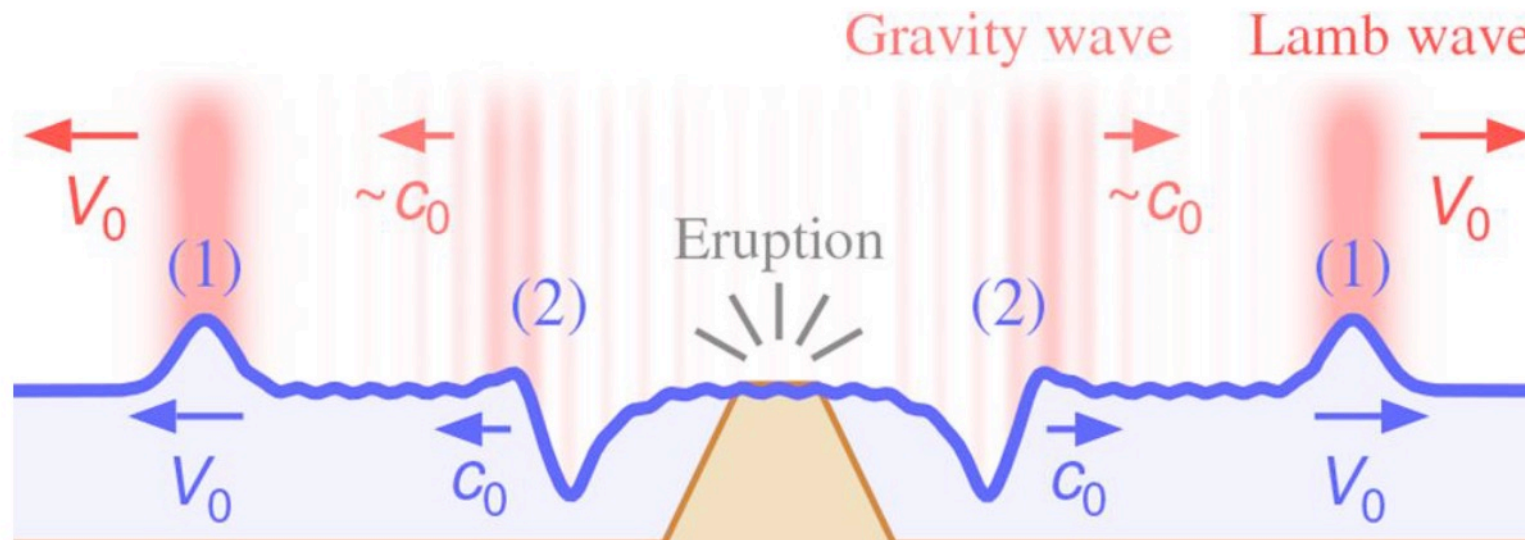
(1) Forcibly-displaced wave by Lamb wave (V_0)

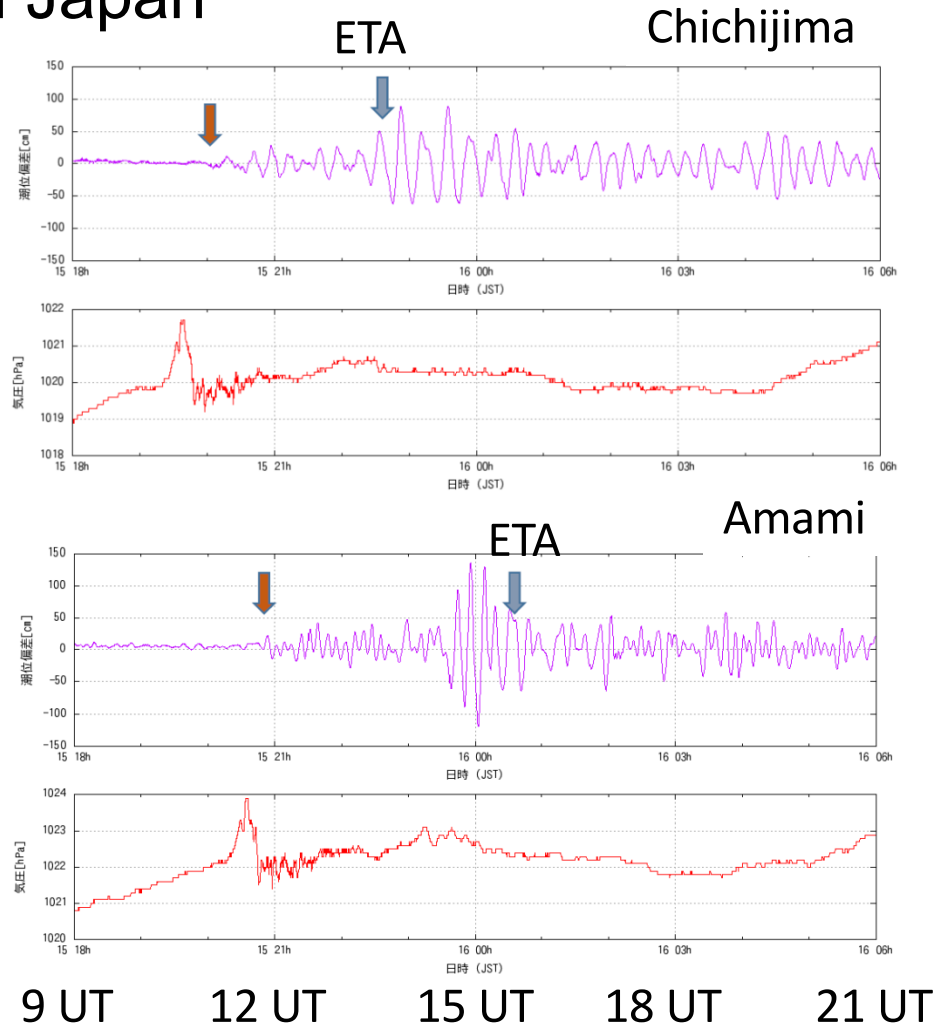(2) Ocean gravity waves ($c_0 \sim (g_0 h)^{0.5}$)

   (2a) Subsidence wave, which compensates uplift by Lamb wave

   (2b) Waves displaced by atmospheric gravity wave modes
       with resonance effect

   (2c) Waves by crustal deformation around the volcano

Kubota et al. (2022)

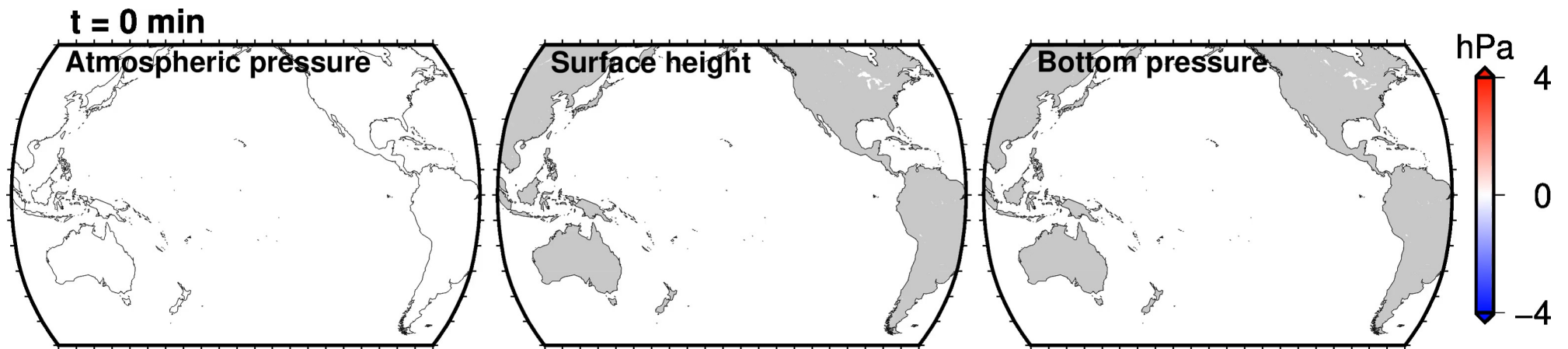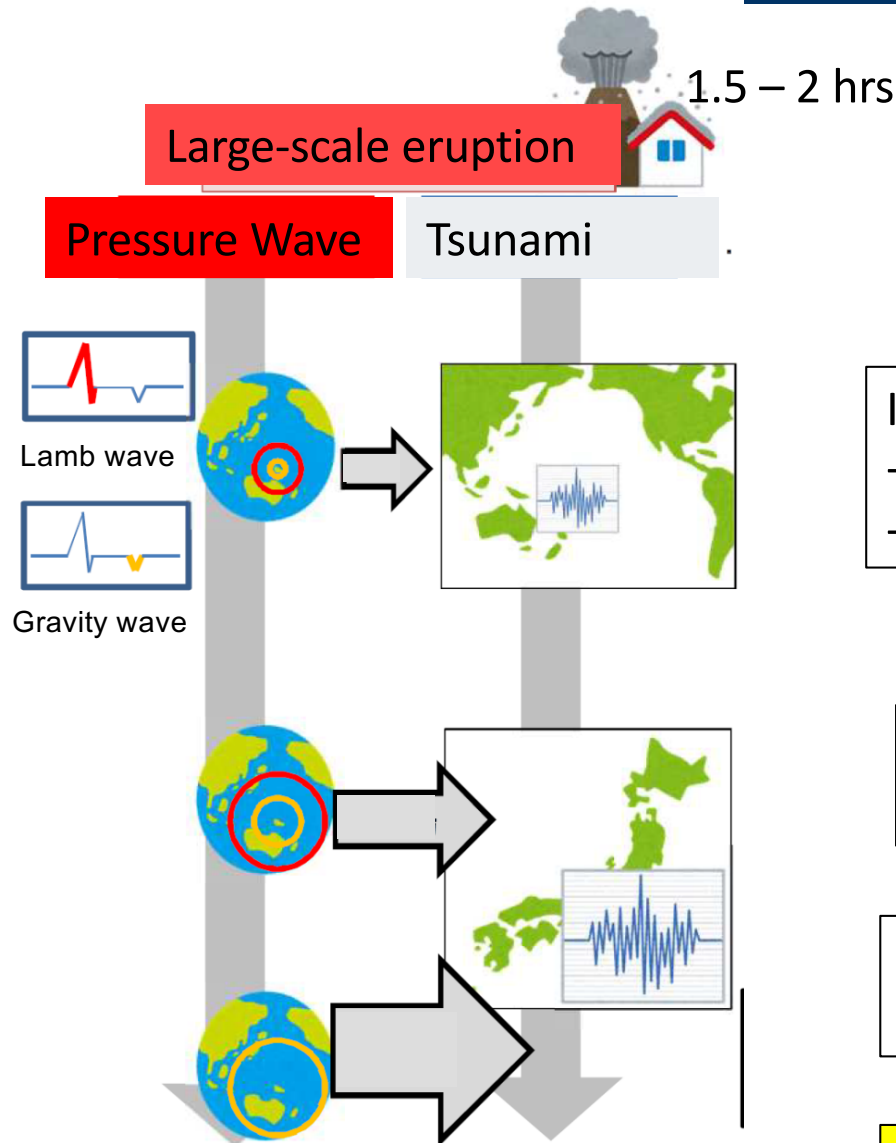# Hunga Tonga- Hunga Ha'apai eruption 2022

Kubota et al. (2022)

Hunga Tonga- Hunga Ha'apai eruption 2022

1.5 – 2 hrs

Large-scale eruption

Pressure Wave

Tsunami

Lamb wave

Gravity wave

Information on far-field earthquakes [A]
- Large scale volcanic eruption
- Possibilities of tsunami generation

Information on far-field earthquakes [B]
- Tsunami observation on foreign tide gauges
- Analysis of Himawari image

Yes

Tsunami obs in Japan ?

No

Tsunami warning/advisory

No tsunami observation

Update of Tsunami warning/advisory

No tsunami damage expected

clearance

enter

© Japan Meteorological Agency

Thank You

Kenji Satake
University of Tokyo
satake@eri.u-tokyo.ac.jp