3rd International Workshop on Waves,
Storm Surges, and Coastal Hazards
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Tidal oscillations (meteo-tsunami) generated by Tonga volcano eruption

Nadao Kohno [1)], Hiroaki Tsushima [1)], Yutaka Hayashi [1)], and Mikhail Entel [2)]

[1)] Meteorological Research Institute, JMA

[2)] Bureau of Meteorology

nkohno@mri-jma.go.jp, nkono@met.kishou.go.jp

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  - Volcanic eruption and unexpected tsunamis
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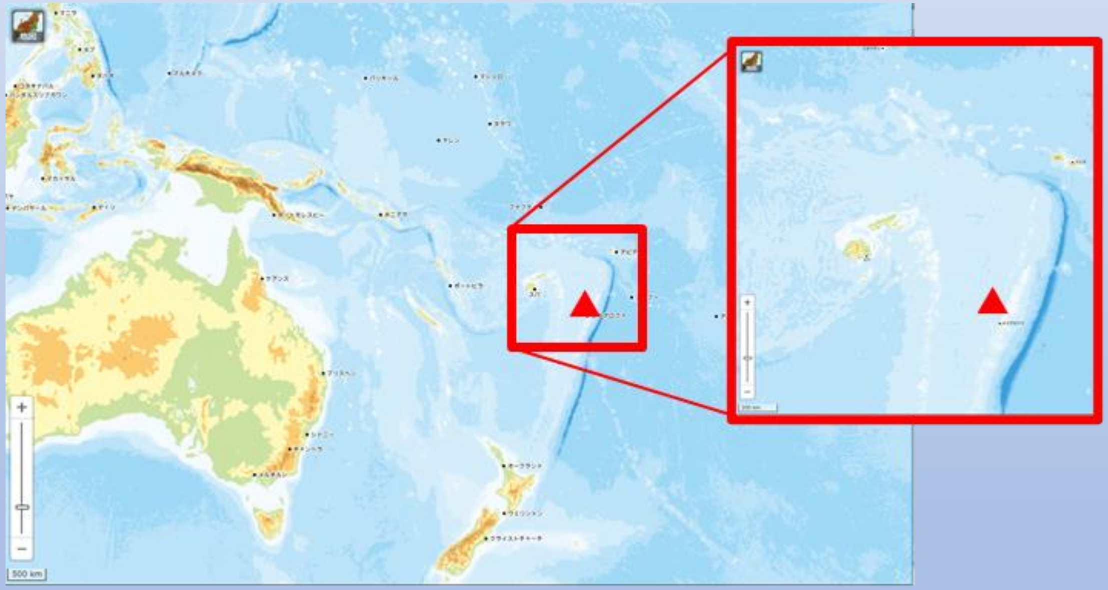
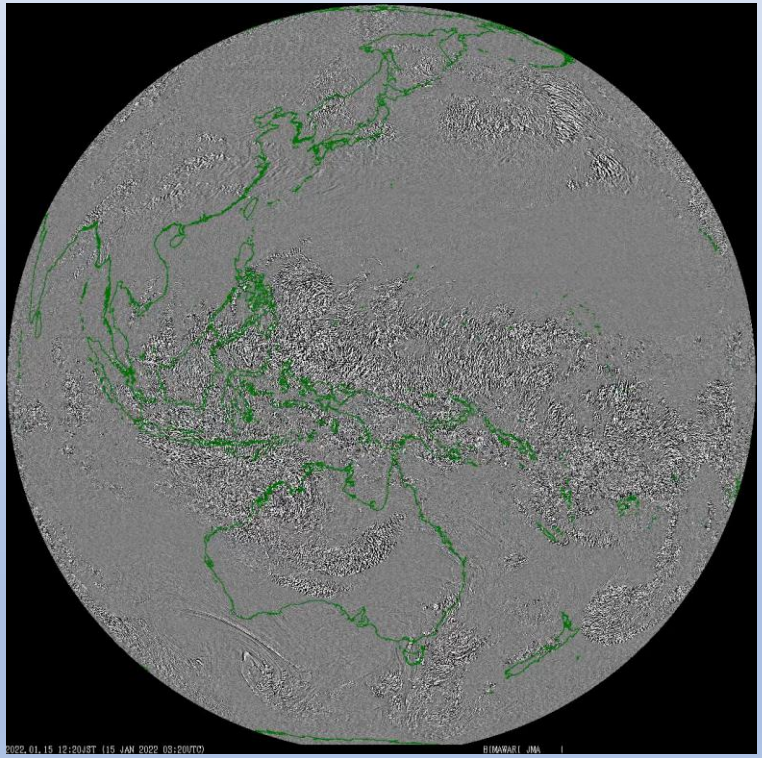
Volcanic eruption

- Volcano: Hunga Tonga-Hunga Ha’apai (a submarine volcano)
- Time of occurrence: 13:15 JST (04:15UTC) on 15 January 2022
- Volcanic Explosivity Index (VEI): 5
- Volcanic plume height：52,000 feet (16,000 m)

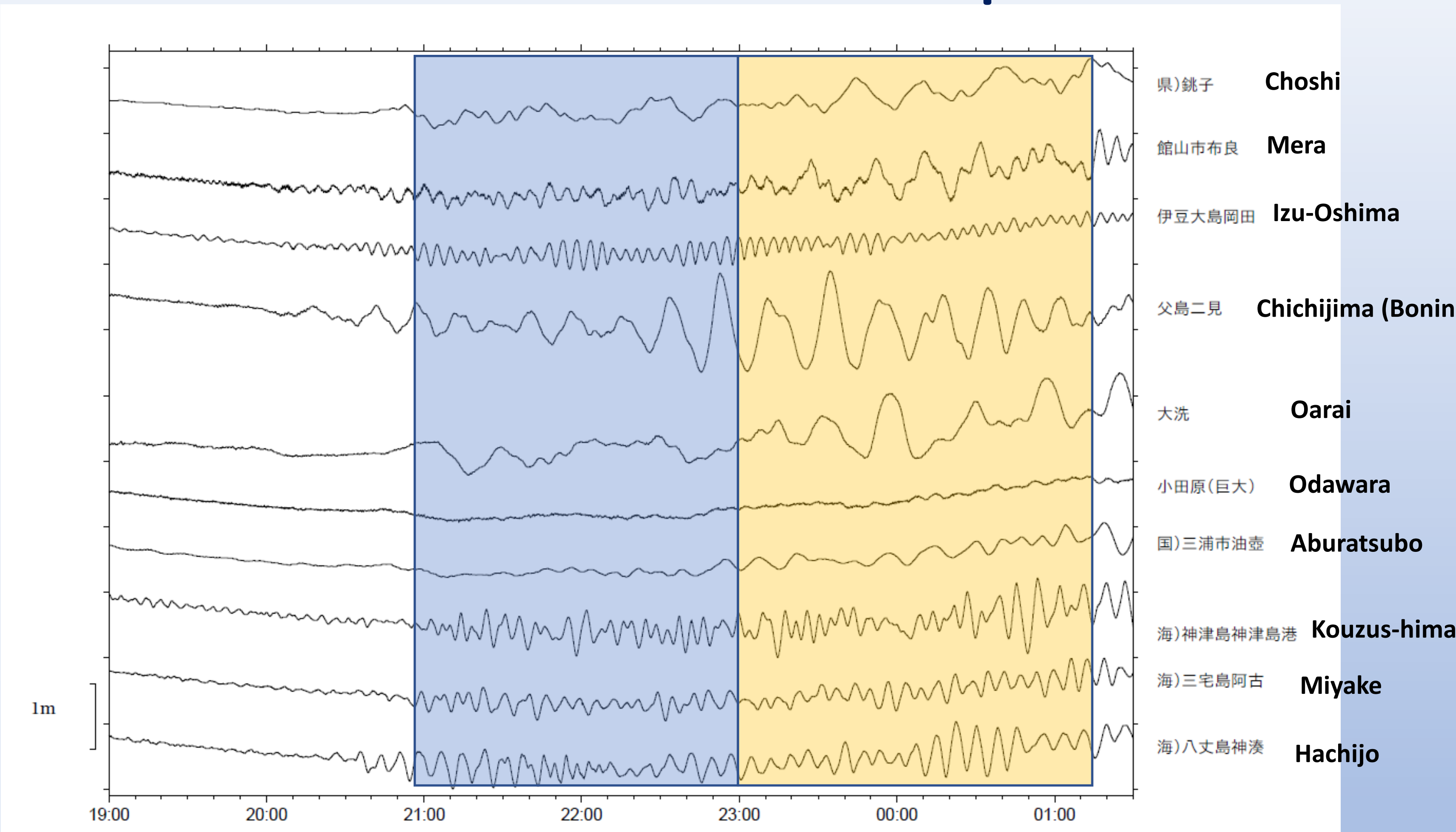


Hunga Tonga-Hunga Ha’apai



Water vapor images by Geostationary Meteorological Satellite Himawari (Meteorological Satellite Center, JMA)

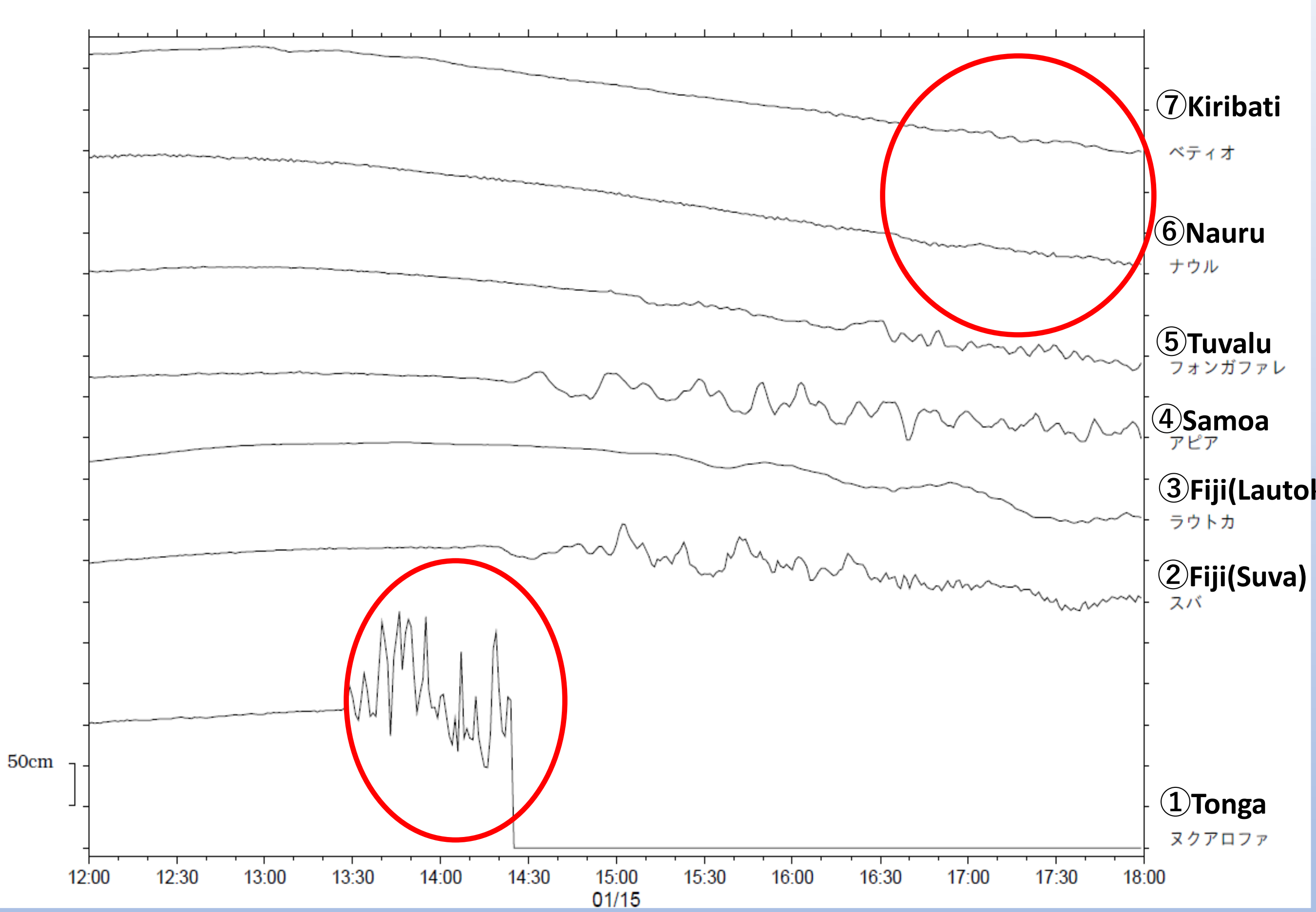
Tide observations in Japan

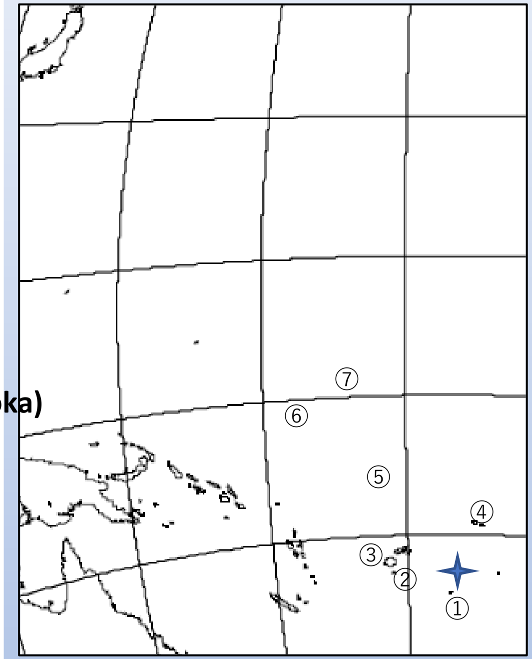


気象庁報道発表資料（2022年1月16日）より

- ✓ Oscillation happened around 21:00 JST
(2 hours earlier than expected arrival times)
- ✓ Large amplitudes were observed in 23:00 JST (Bonin Is.) ~ 24:00 JST (main Is.)
(Much larger than estimated amplitudes)

Tide observations in South pacific



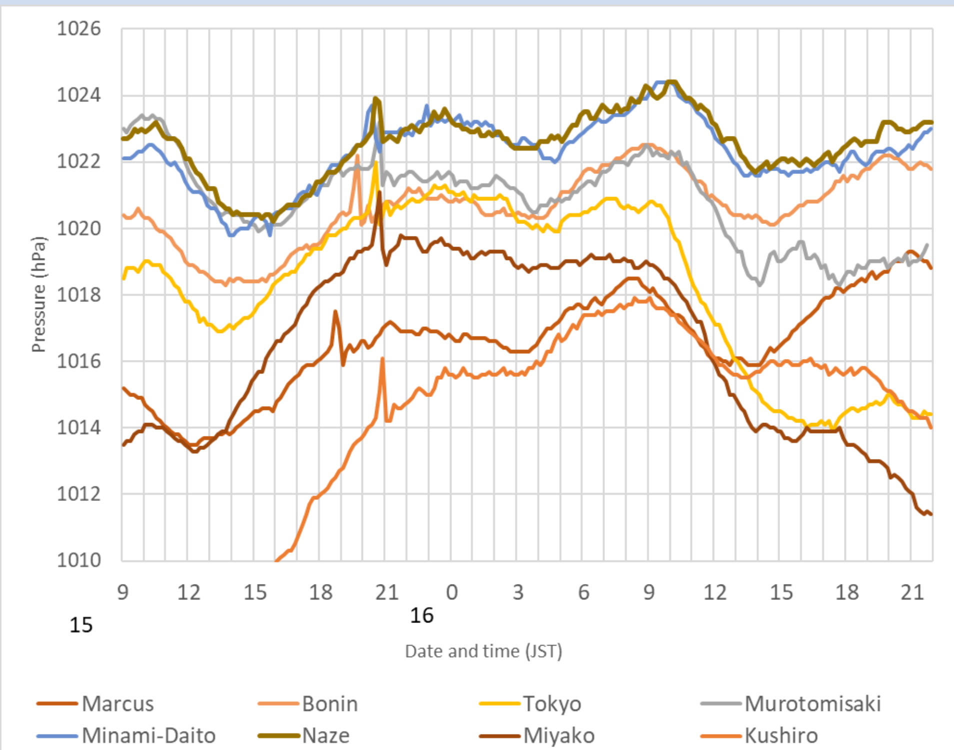


JMA (16, Jan, 2022)

- Amplitude at Nuku‘alofa (Tonga) was at most 1m.
- No tidal oscillation was observed at Nauru and Kiribati.

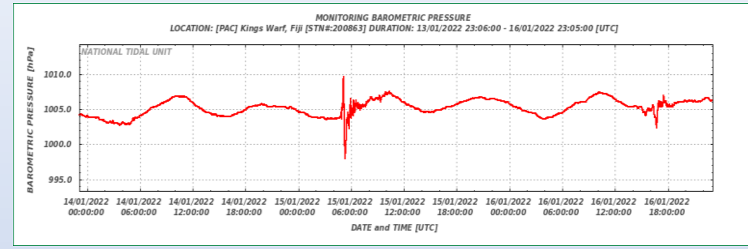
Observed pressure changes

- Sudden pressure changes were observed in many stations in Japan and south Pacific
- The changes are associated by the eruption
- The pressure differences are ±5~10hPain south Pacific and around 2hPa in Japan

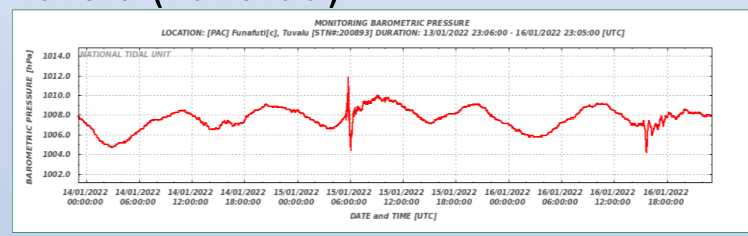


Stations in Japan

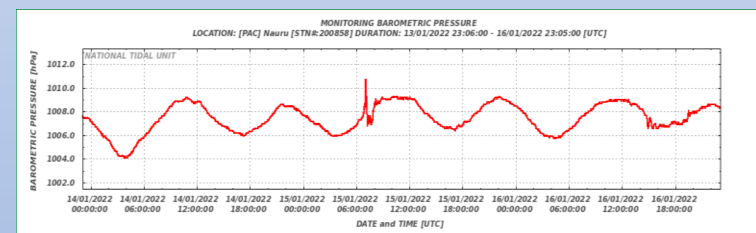
Fiji (Suva)



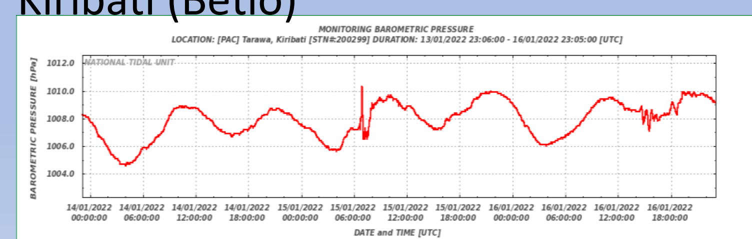
Tuvalu (Funafuti)



Nauru



Kiribati (Betio)



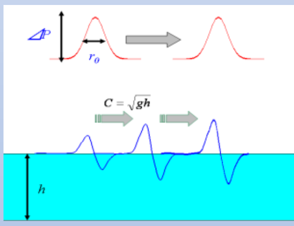
Meteotsunamis

IOC glossary 2019: **Meteorological tsunami (meteotsunami)**

Tsunami-like phenomena generated by meteorological or atmospheric disturbances. These waves can be produced by atmospheric gravity waves, pressure jumps, frontal passages, squalls, gales, typhoons, hurricanes and other atmospheric sources. Meteotsunamis have the same temporal and spatial scales as tsunami waves and can similarly devastate coastal areas, especially in bays and inlets with strong amplification and well-defined resonant properties.

■Main mechanism: Proudman resonance **(Proudman, 1929)**

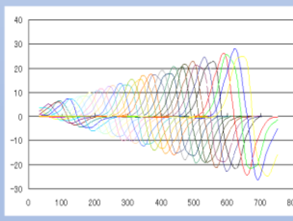
Moving pressure disturbances generate shallow water gravity waves in ocean. The amplifying factor R becomes large when moving speed pf pressures is near to the phase speed of the ocean gravity



$$R = \frac{1}{1-\left(\frac{V}{c}\right)^2} = \frac{1}{1-\frac{V^2}{gh}}$$

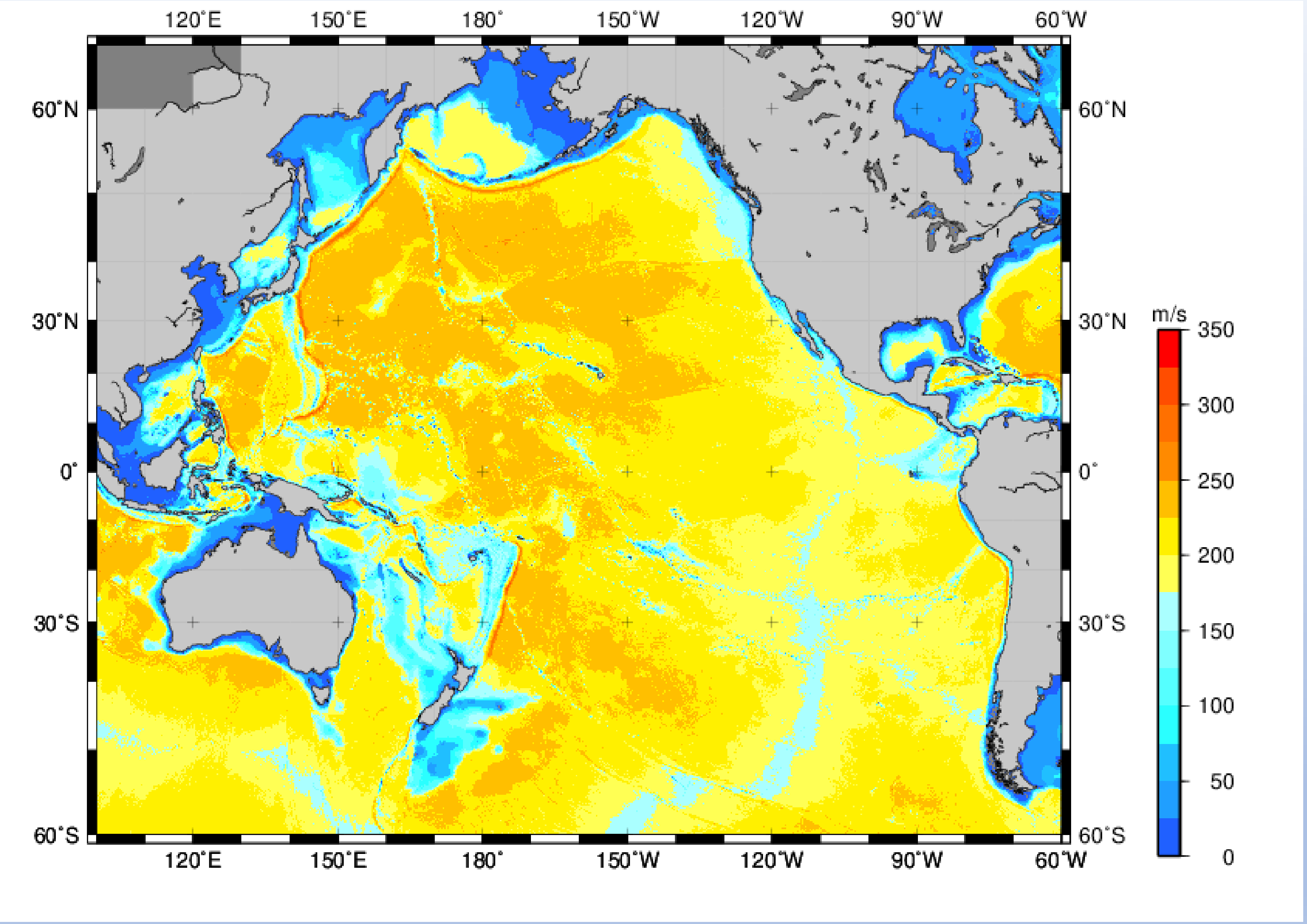
V: moving speed of pressure waves, $c = \sqrt{gh}$: phase speed of shallow water waves

(g: gravitational acceleration, h: water depth)



- ✓ Dynamically amplified, unlike storm surges
- ✓ Other effects like Green's law may be included, same as usually tsunamis.

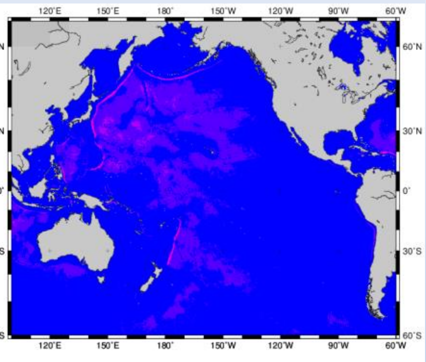
Phase speeds of shallow water waves



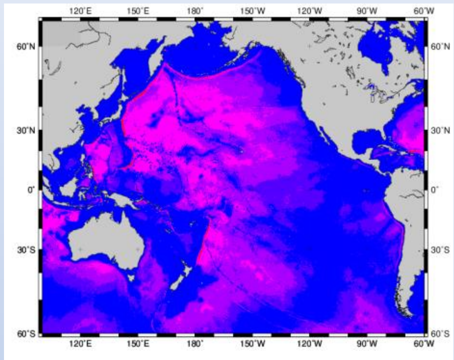
Phase speeds(m/s) of shallow water gravity waves calculated from water depth. (depth data: NGDC ETOPO2v2)

Possibility of resonance

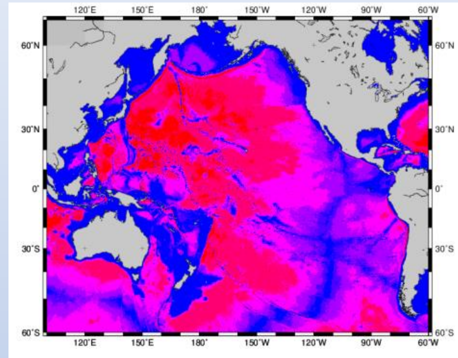
The ratio of moving speed of pressures and phase speed of shallow-water gravity waves (Froude number).



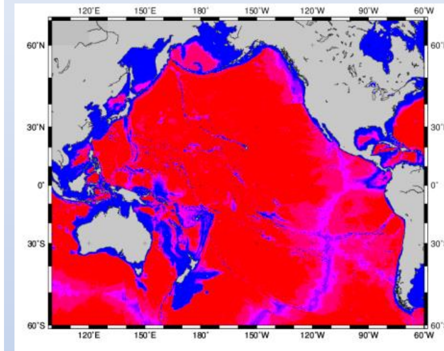
340m/s



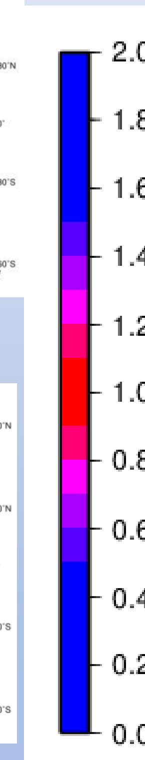
300m/s

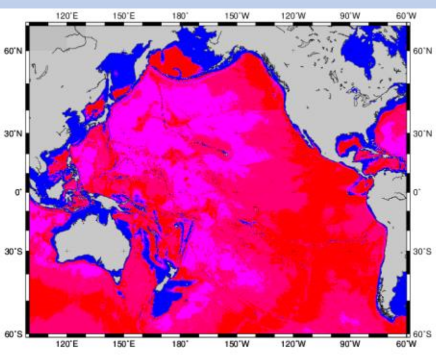


260m/s

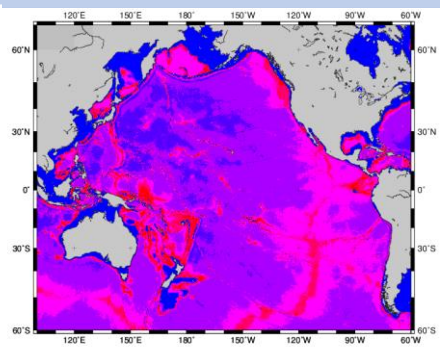


220m/s

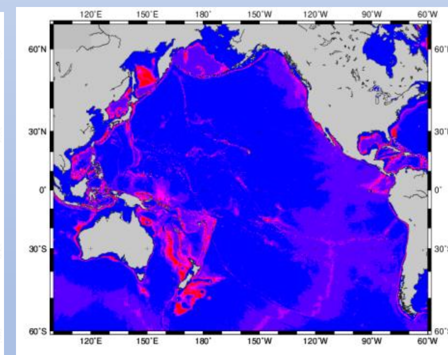




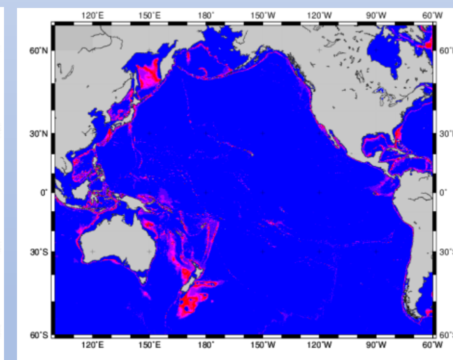
180m/s



160m/s



120m/s



80m/s

The preferable condition for Proudman resonance in the Pacific is
<u>Moving speeds of pressure are 160~300m/s</u>

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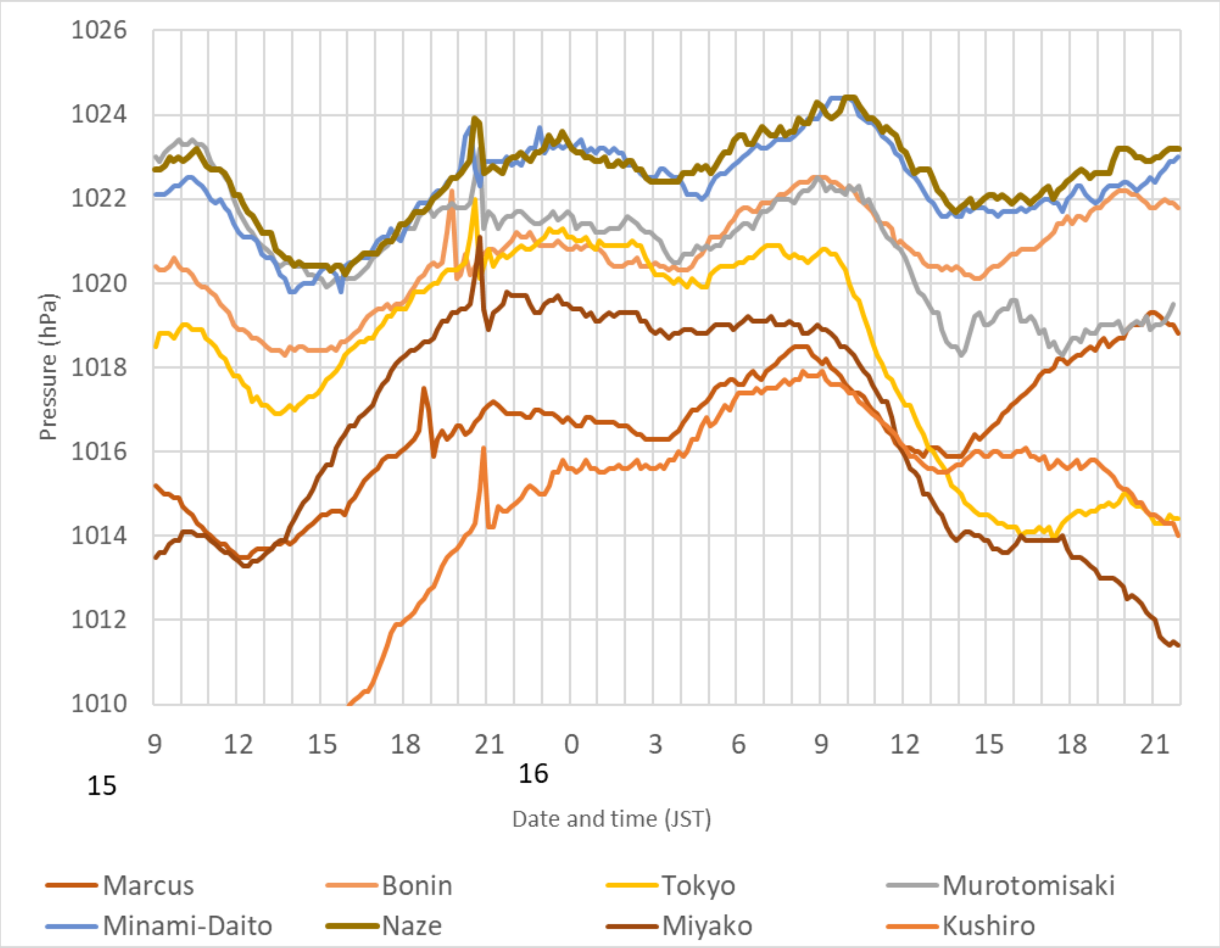
Observed pressures in Japan

- Surface pressures



Observed time of the peaks

Marcus
1017.5hPa (18:40)
1015.9hPa (19:00)

Bonin
1022.0hPa (19:40)
1020.1hPa (19:50)

Tokyo
1022.0hPa (20:30)
1020.1hPa (20:40)

Murotomisaki
1023.2hPa (20:40)
1021.3hPa (20:50)

Minami-Daito
1023.5hPa (20:10)
1022.7hPa (20:30)

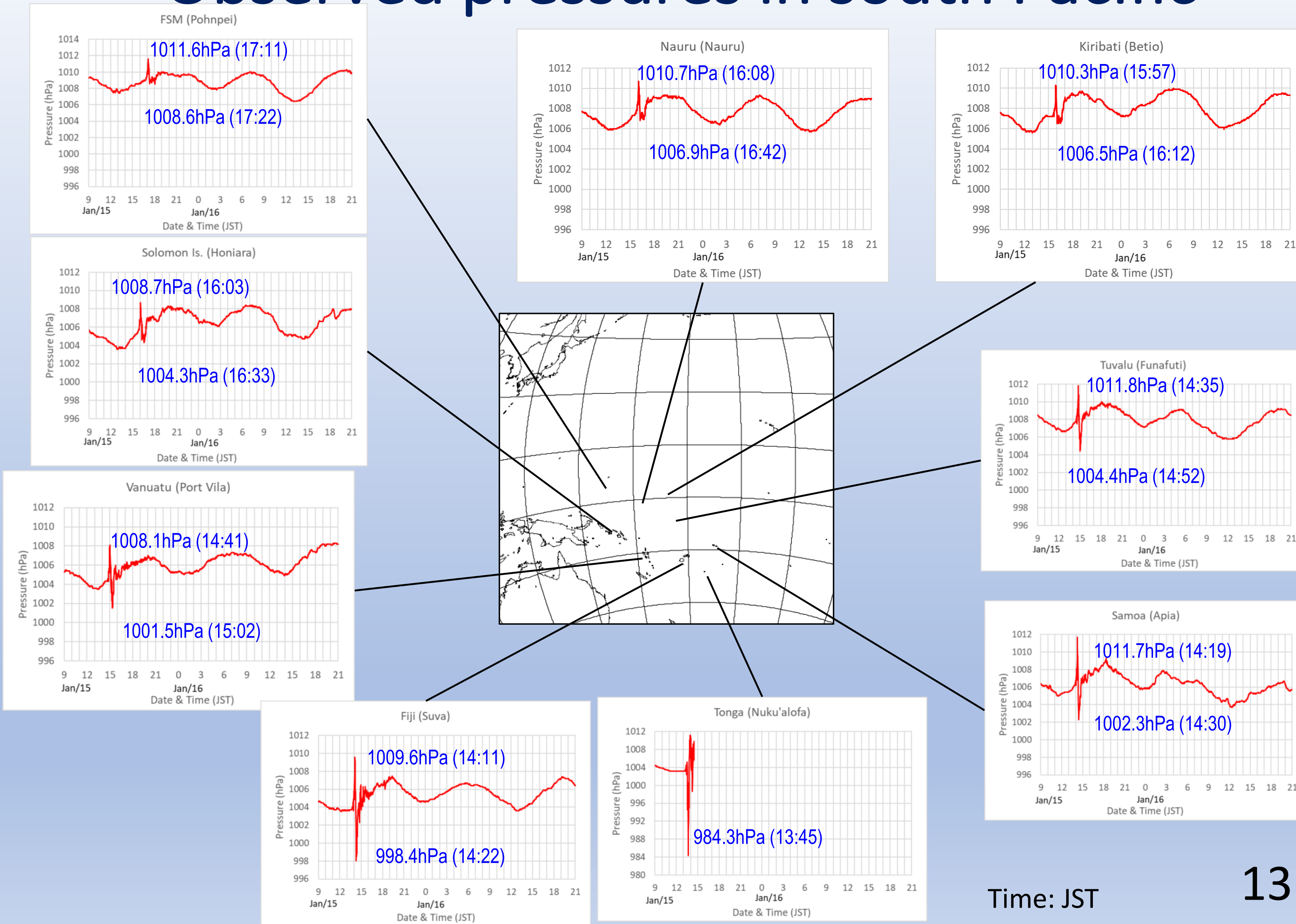
Naze
1023.9hPa (20:30)
1022.6hPa (20:50)

Miyako
1021.1hPa (20:40)
1018.9hPa (21:00)

Kushiro
1016.1hPa (20:50)
1014.2hPa (21:00)

※JSTT

Observed pressures in south Pacific

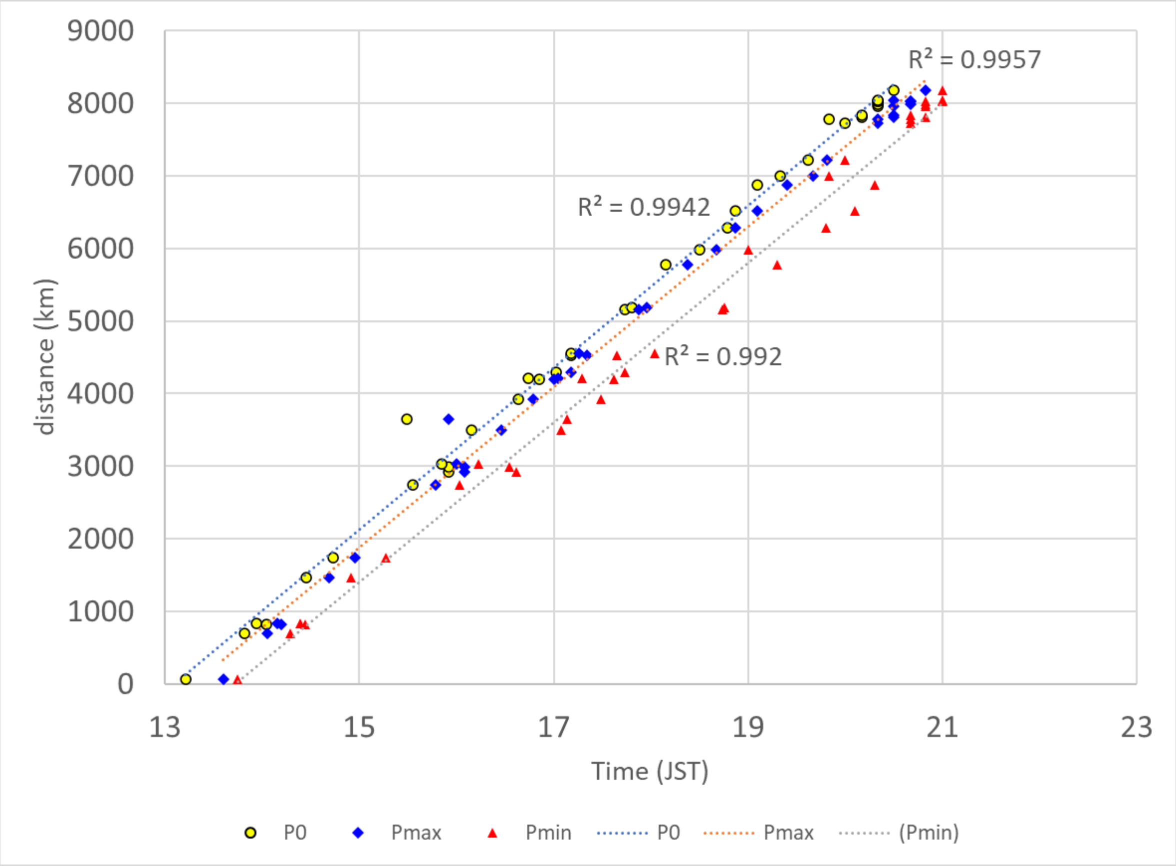


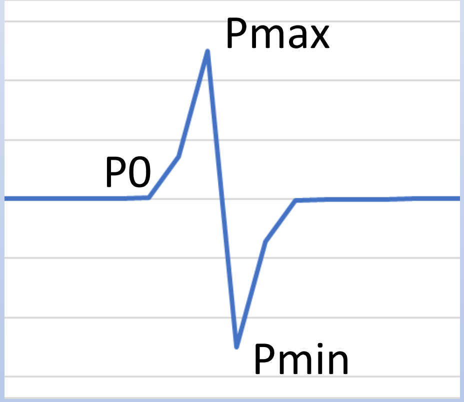
Time: JST

Moving speed of the atmospheric pressures

- Measuring moving speed from observed pressures
  - ➢ The time of eruption is known(13:15JST on 15 Jan.), but the exact time of pressure wave generation is not clear (The time of eruption can not be used as the start.)
  - ➢ The location (20.55S, 175.385W), and the observation points and times are certain.

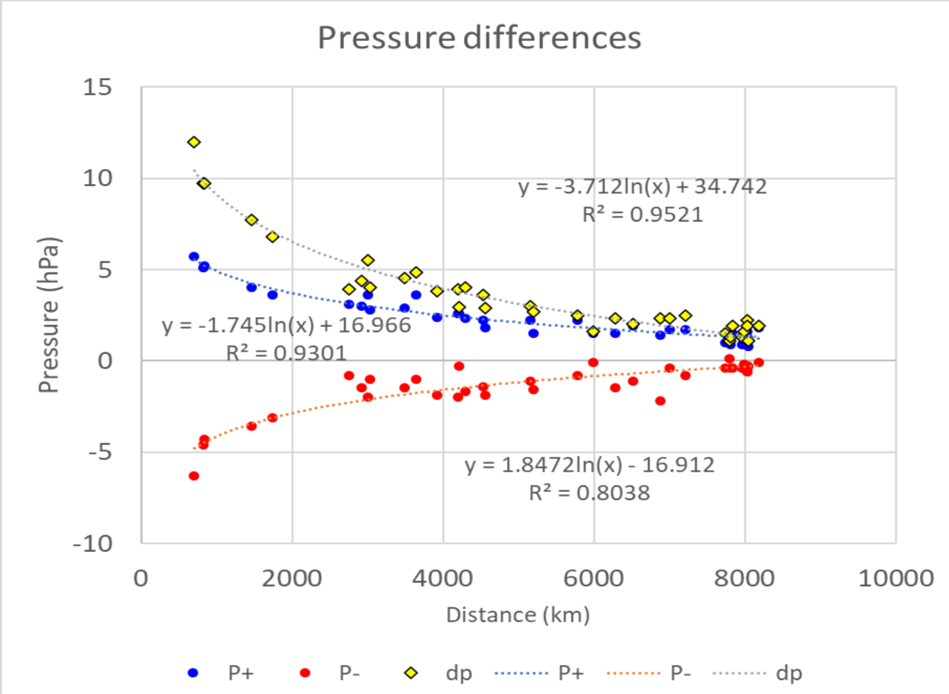
⇒ Moving speed can be estimated from the distance from the eruption and time of observations.

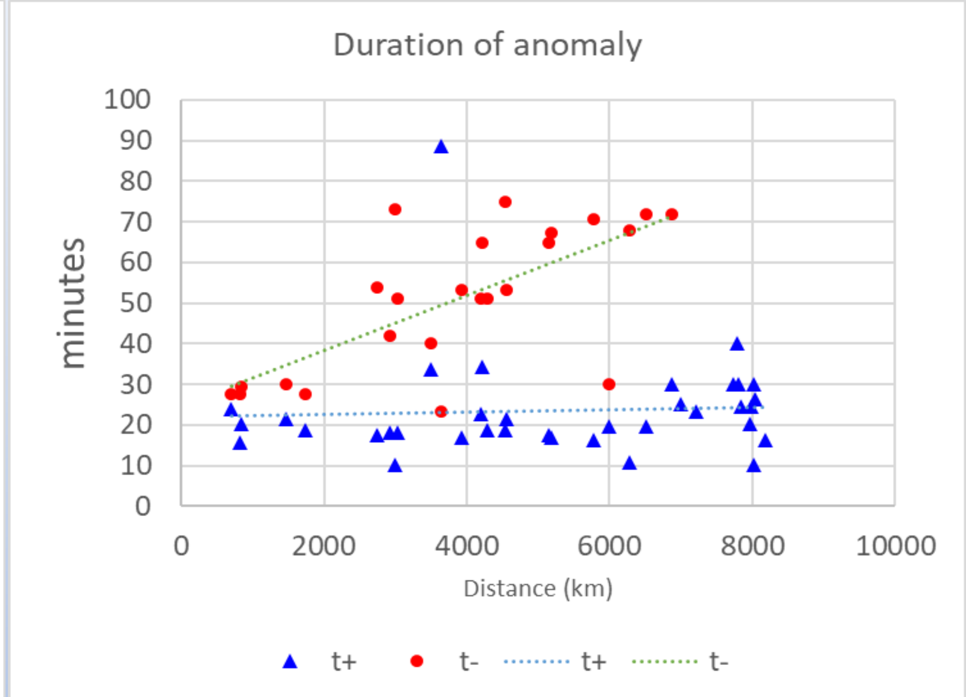




- ✓ Moving speeds are can be regarded as constants (R>0.99).
- ✓ Moving speed of P0, pmax, Pmin are 310m/s, 307m/s, 304m/s, respectively
- ✓ Initial time (y0) could be 13:07 ~ 13:45

Change of pressure values





P+: positive values, P-: negative values
dp: the maximum difference (= P+ - P-)

t+: duration of positive values,
t-: duration of negative values

- ✓ Amplitudes become smaller as distance longer
- ✓ Negative values are hard to measure due to complicated shapes and may have large errors.
- ✓ Pressure changes can be expressed as logarithmic functions

- ✓ Duration of t+ is almost constant
- ✓ Duration of t- becomes large in time (can be expressed by a linear regression
- ✓ Negative values over 7000km are excluded (too small to detect)

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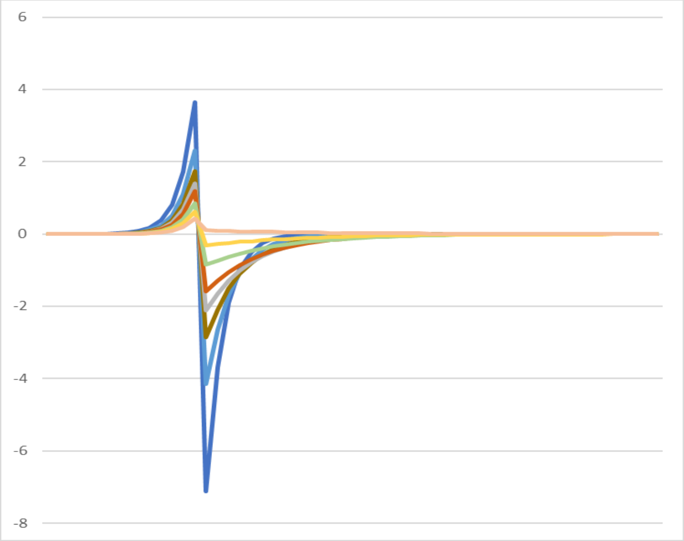
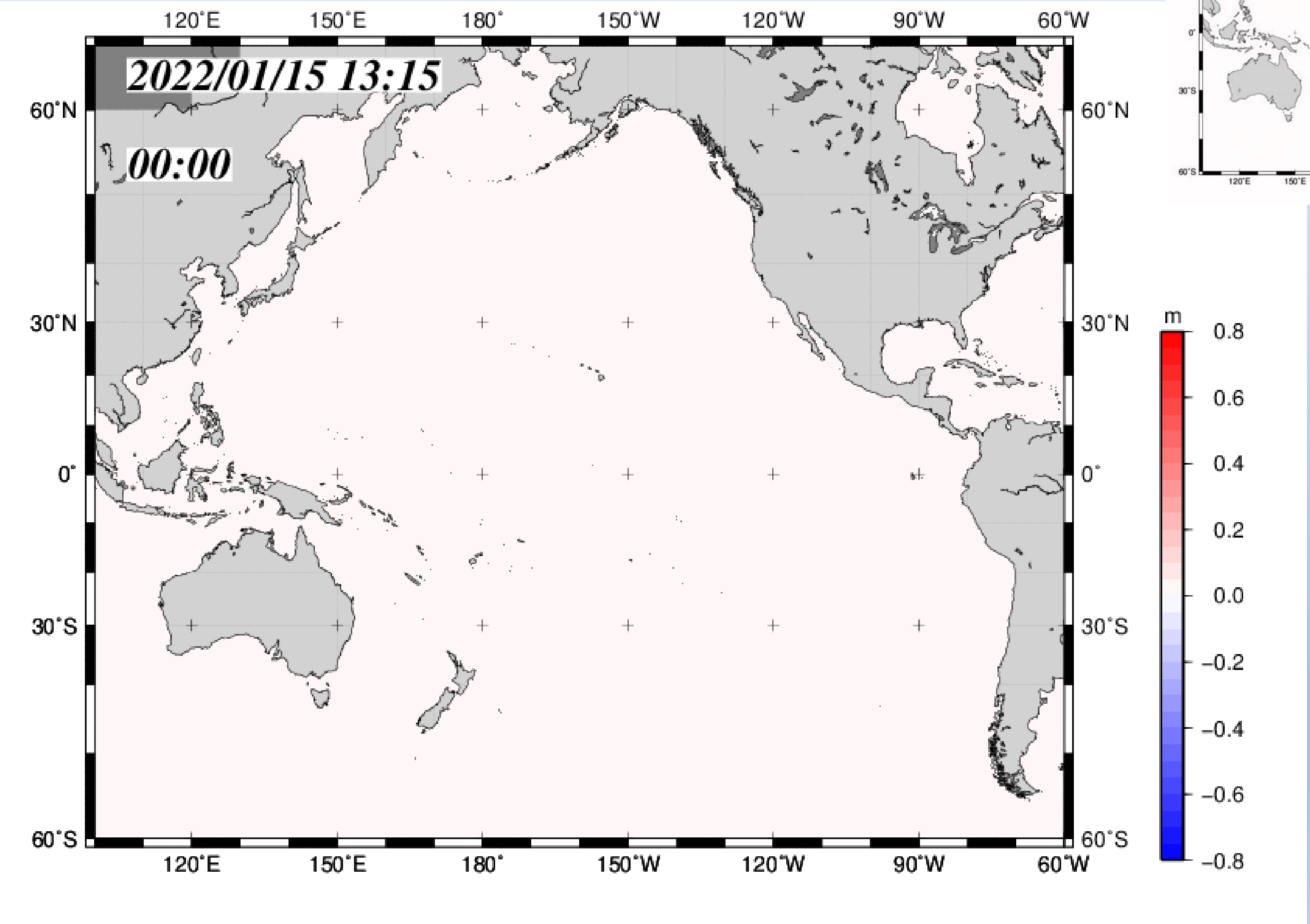
Setting of numerical simulations

- Model: 2-dimensional shallow water model on spherical coordinate
- Area: -60.0 - 66.0 (Latitude), 100.0 – 300.0 (Longitude)
- Resolution: 2 minutes (3.7 km)
- Bottom friction: Manning's roughness coefficient (0.025), water depth $^{7/3}$
- Initial condition: static state
- Calculation: 24 hours
- Forcing: Symmetric pressure disturbance
  - Moving speed: 305 m/s
  - Anomaly: logarismically decreasing

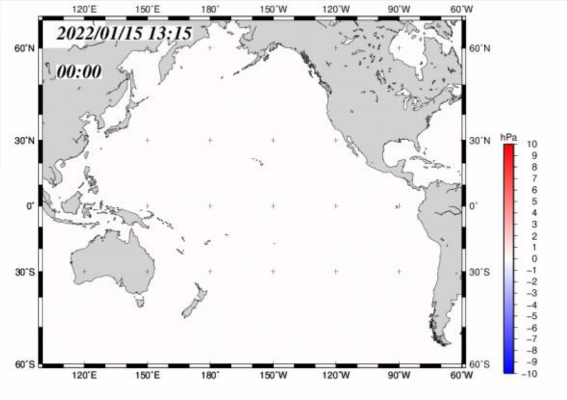


Blue → red

Simulation results



Water level changes (tidal oscillations = tsunamis)

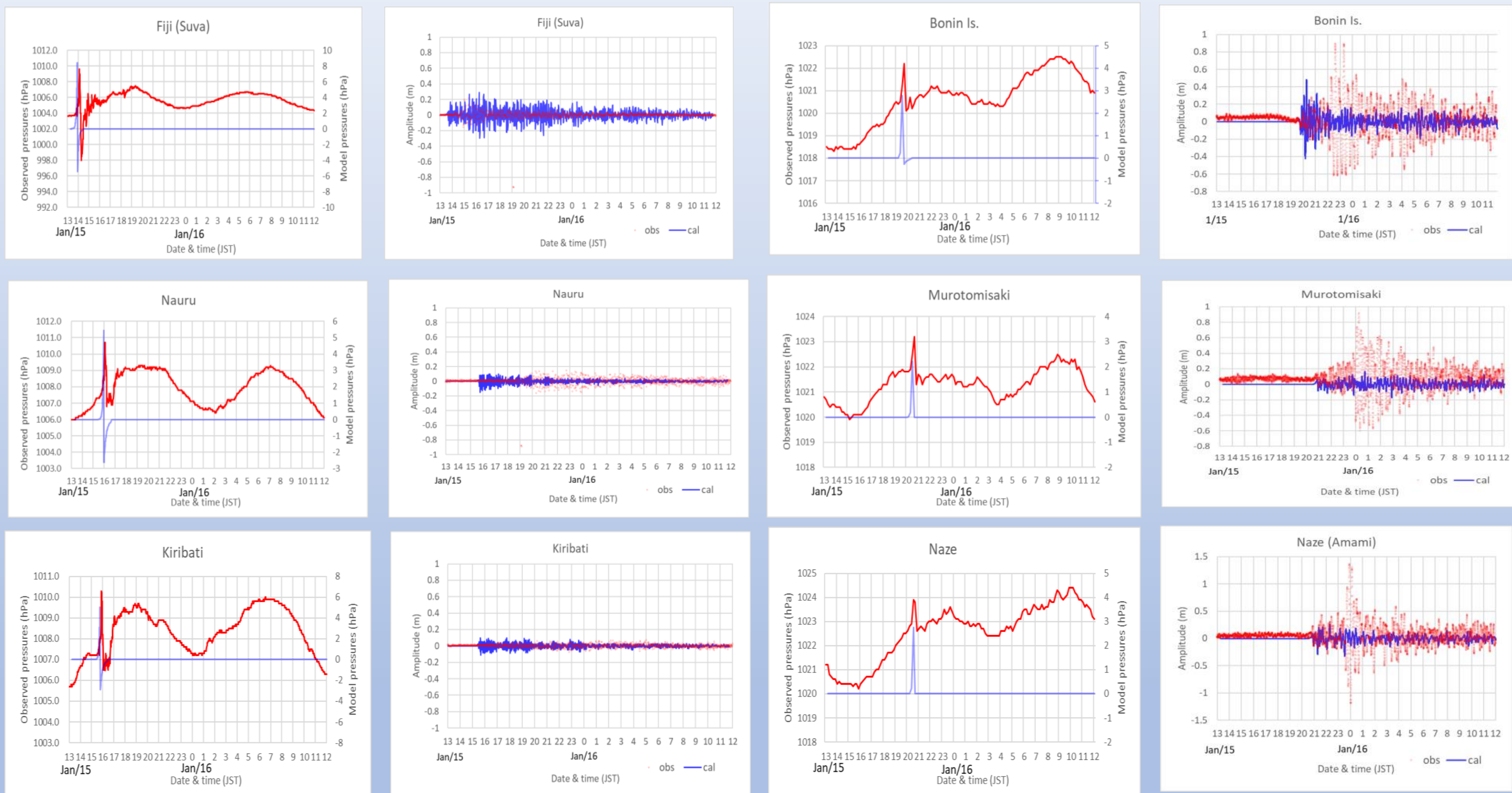


Pressure (forcing)

Comparison at coastal points

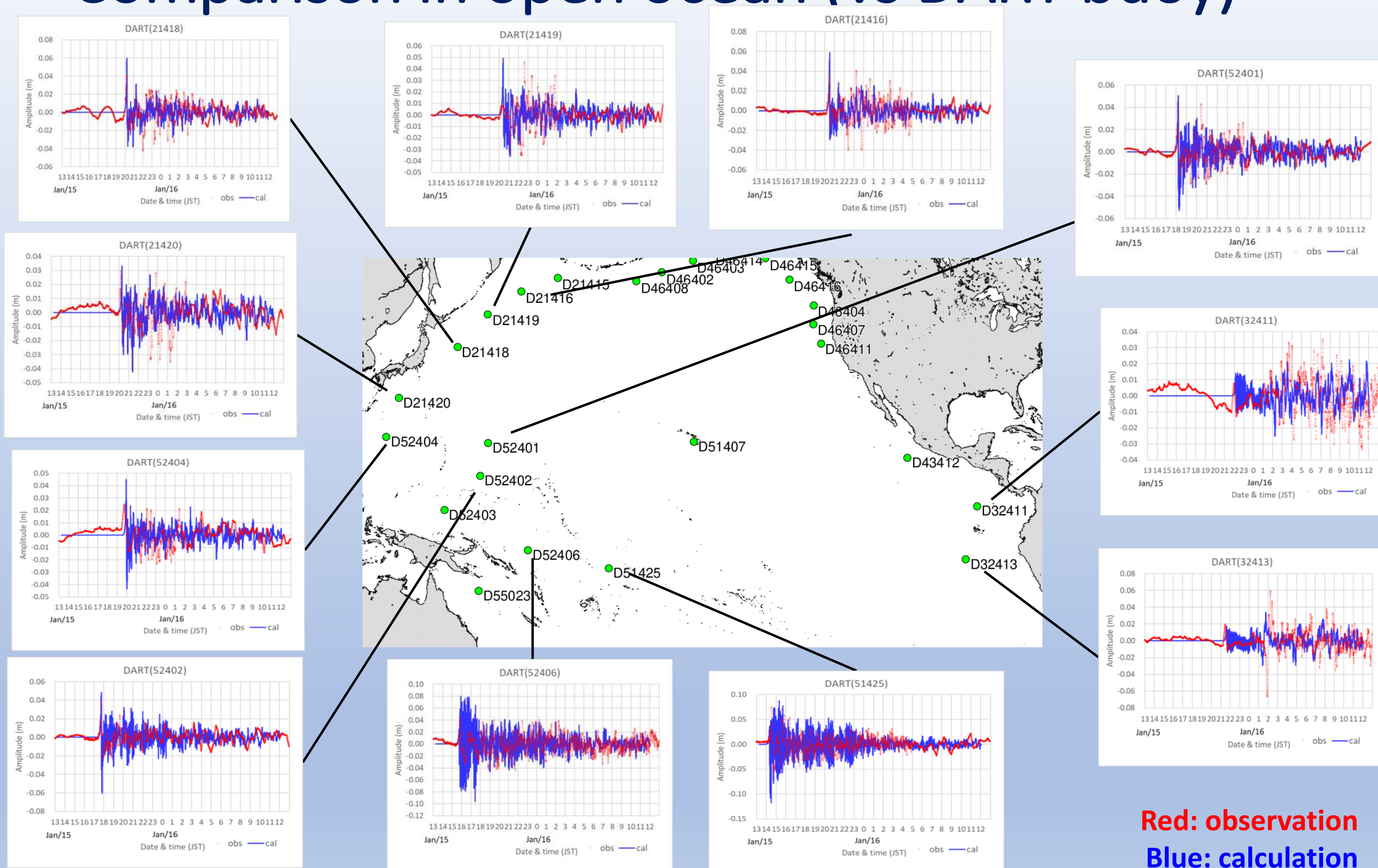
Pressures (left) and tides(right)

Red: observation **Blue: calculation**



- Pressures (forcing) in the calculation is basically same
- Timing of tidal oscillation looks the same in all points
- Amplitudes of tides are large in south Pacific and small in Japan

Comparison in open ocean (vs DART buoy)



Red: observation
Blue: calculation

Timing and amplitudes in offshore points are fairly compared, although overestimation are seen near the eruption point.

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Summary

- The oscillations happened in almost whole Pacific (not a local phenomenon)
- In Japan, the oscillation started a few hours earlier, and unexpectedly large amplitudes were observed.
- Atmospheric pressure waves associated with the eruption were observed in Pacific。
  - ✓The moving speed of the pressure, estimated from observations is 305 m/s, which is slightly larger than preferable values for Proudman resonance.
  - ✓Some small pressure fluctuations are seen after that (suitable for the resonance but the amplitudes are very small)
- Simulation with imitated pressure observation was conducted.
  - ✓Simulated results looks basically reasonable in characteristics
  - ✓the timing of tidal oscillation looks same as observation.
  - ✓Amplitudes are similar to observed values in offshore, but underestimations were seen in Japanese coasts.
- The tidal oscillation, especially the first one, can be a kind of meteotsunamis associated by moving pressure waves by the volcanic eruption.

Thank You for attention!

The JMA Mascot "*Harerun*"
(The word "hare" means fine weather in Japanese.)

※A part of this work was supported by *JSPS* KAKENHI *Grant* Number *JP21K21353.*