The Global Reach of the 2022 Tonga Tsunami:
An Overview

津波

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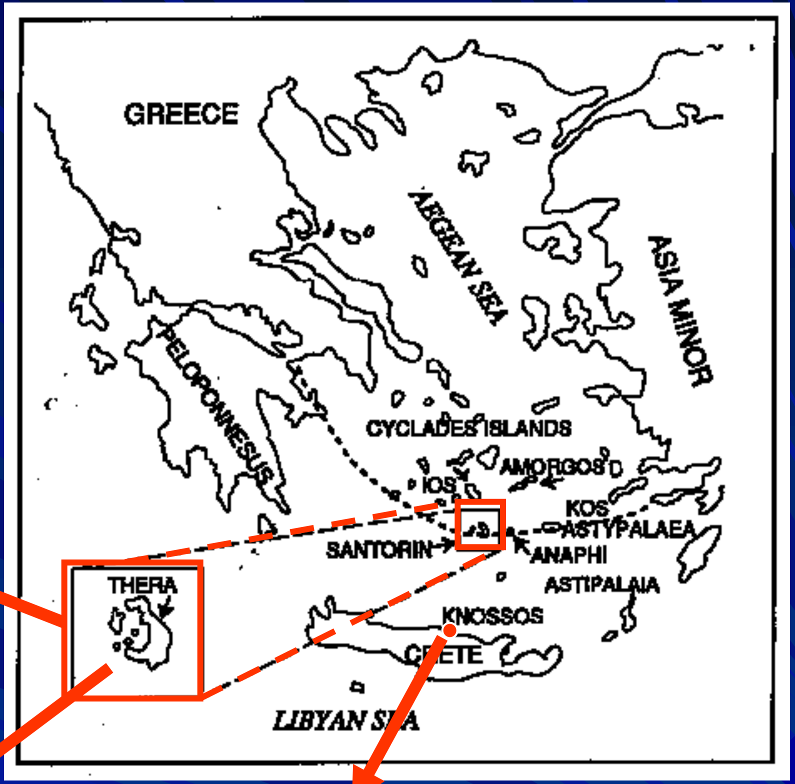
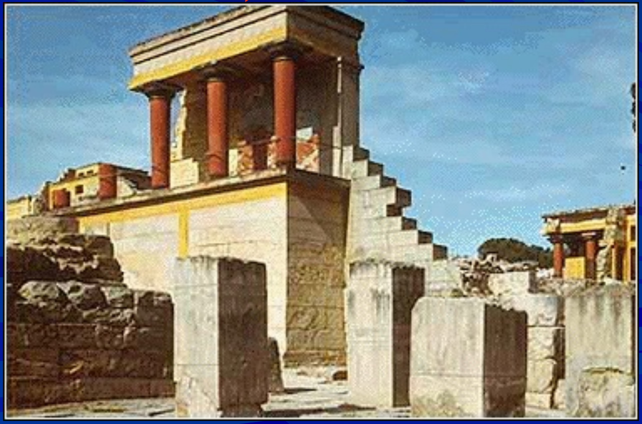
Major volcanic eruptions and tsunamis

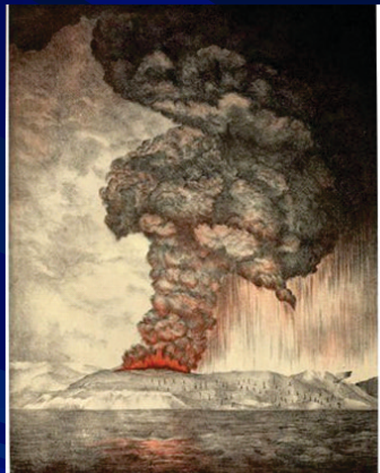
Thera I. (Santorini) 1400 BC
(1650 BC?)





Crete Island, Knossos

Major volcanic eruptions and tsunamis

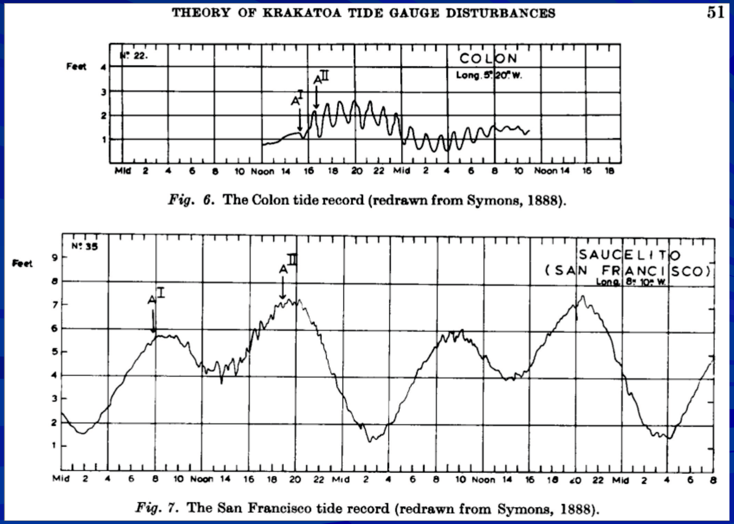


Krakatau, Indonesia (1883)

Before explosion

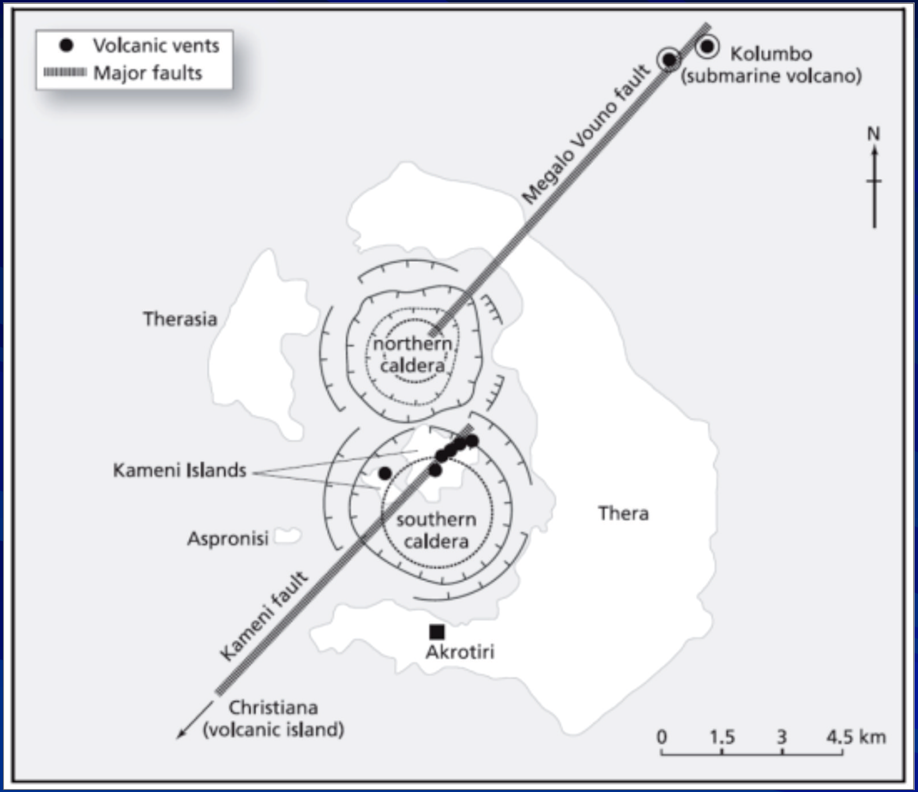
After

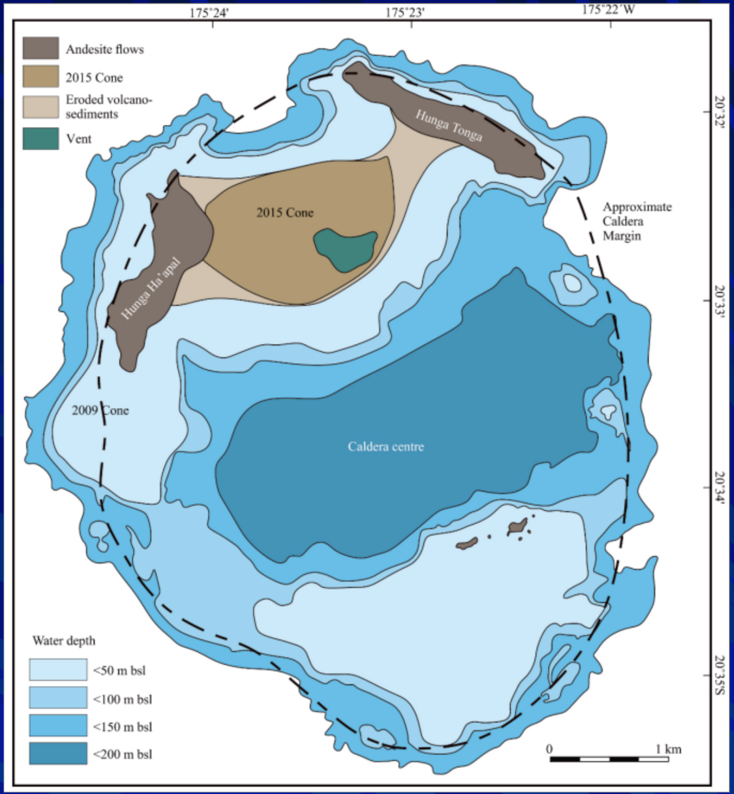
Tide gauge tsunami records



From *Symmons* [1888], *Garrett* [1970]

Santorini and Tonga-Hunga

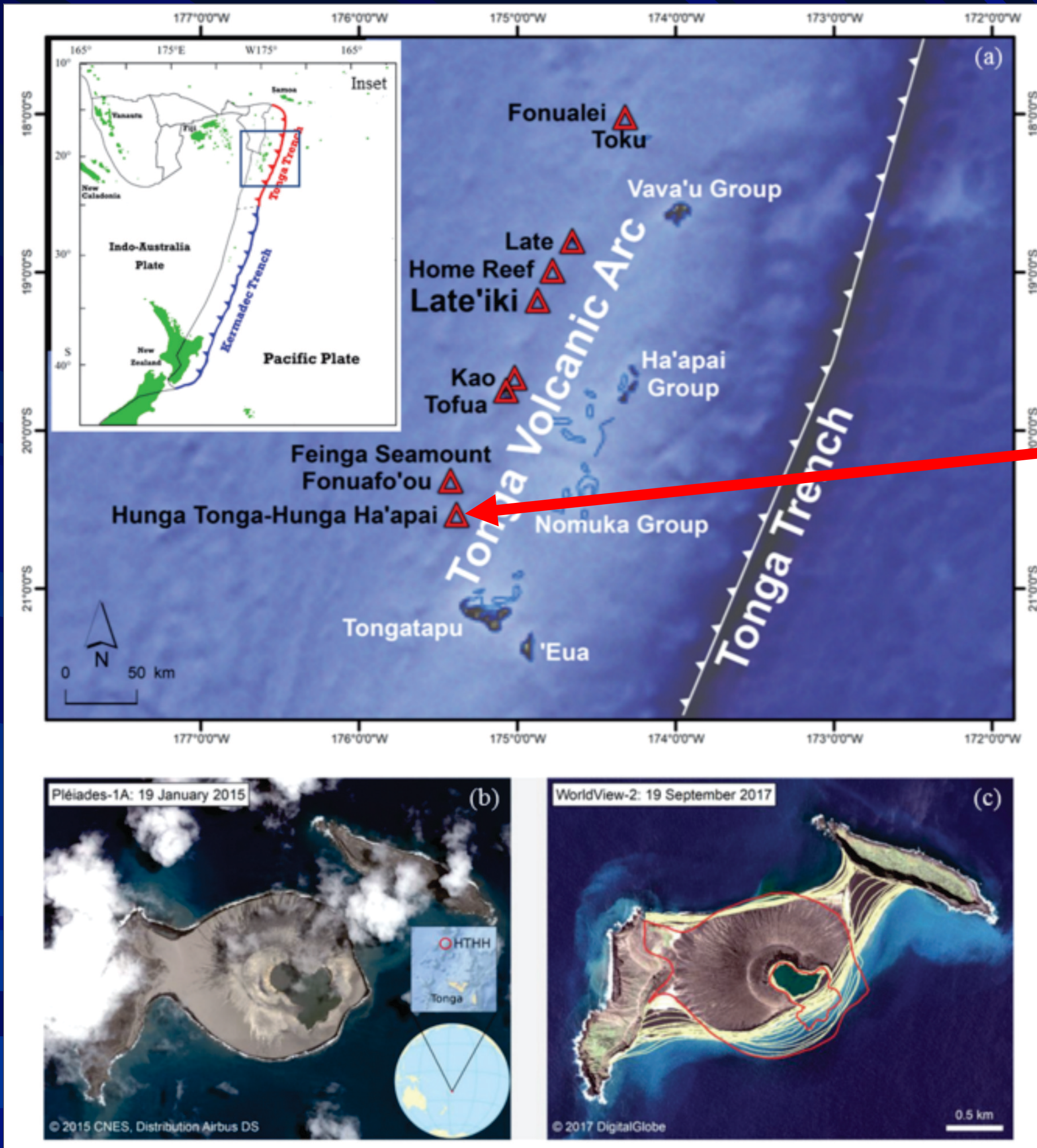




Map of the Santorini archipelago showing the two large calderas, surrounded by the islands of Thera and Therasia, much like Hunga Tonga-Hunga Ha'apai.

Map of the Hunga Tonga-Hunga Ha'apai islands and submarine caldera complex (underwater).

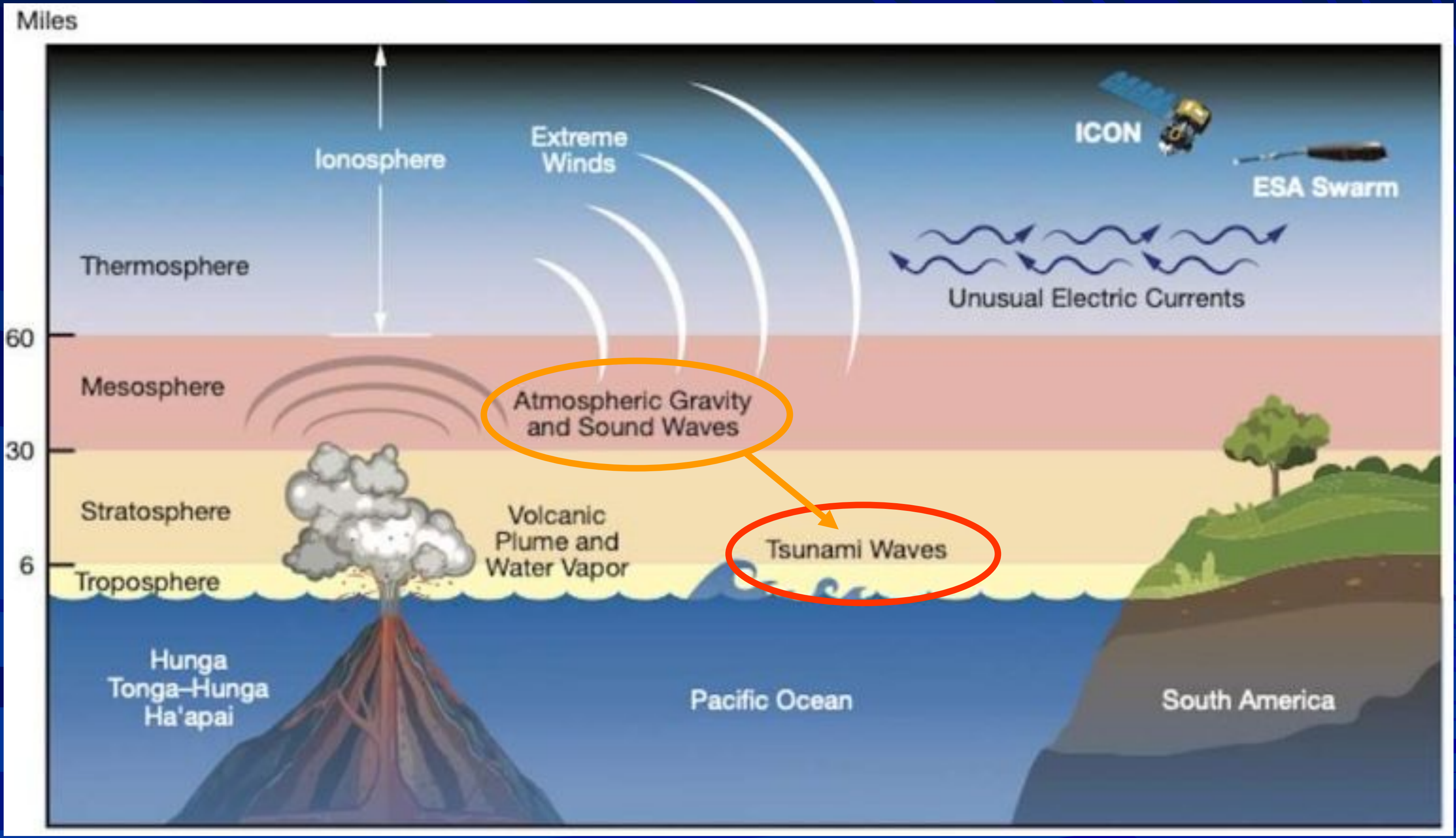
From *Kusky* [2022]



The Tonga Volcanic Arc and two new islands formed in this region in 2014-2019

From *Kusky* [2022]

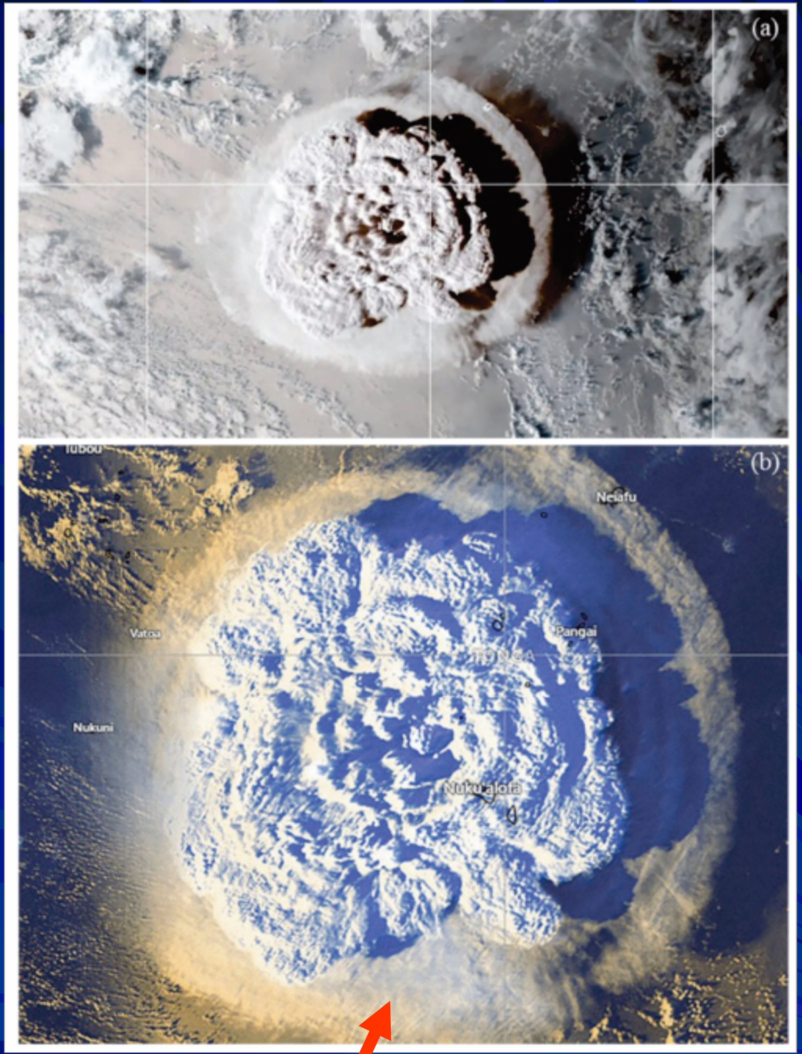
Various geophysical phenomena generated by the 2022 Tonga-Hunga volcanic eruption



The 2022 Tonga-Hunga volcanic eruption

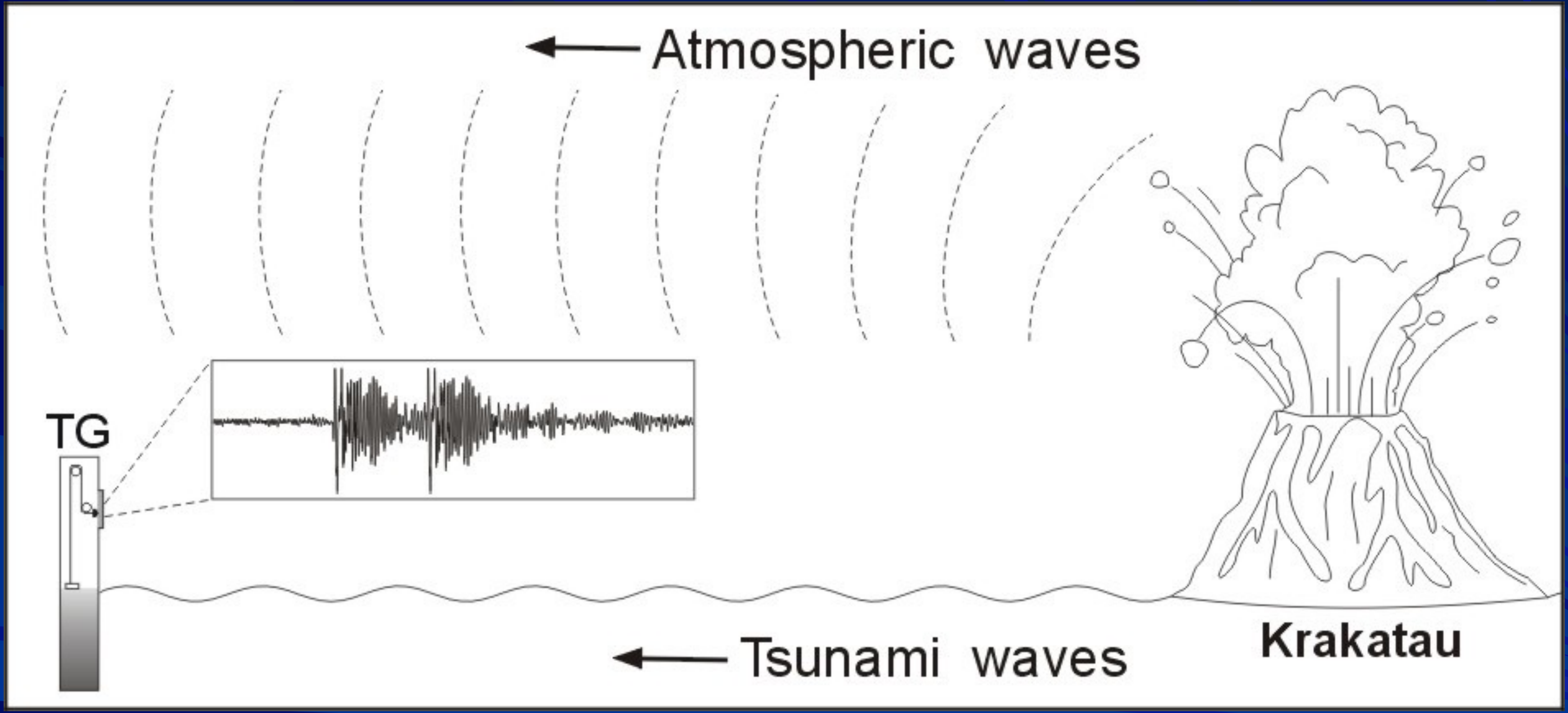
Two photos Service (looking eastward) taken one day before (05:27 UTC, Jan 14, 2022) by the Tonga Geological Service

From *Kusky* [2022]



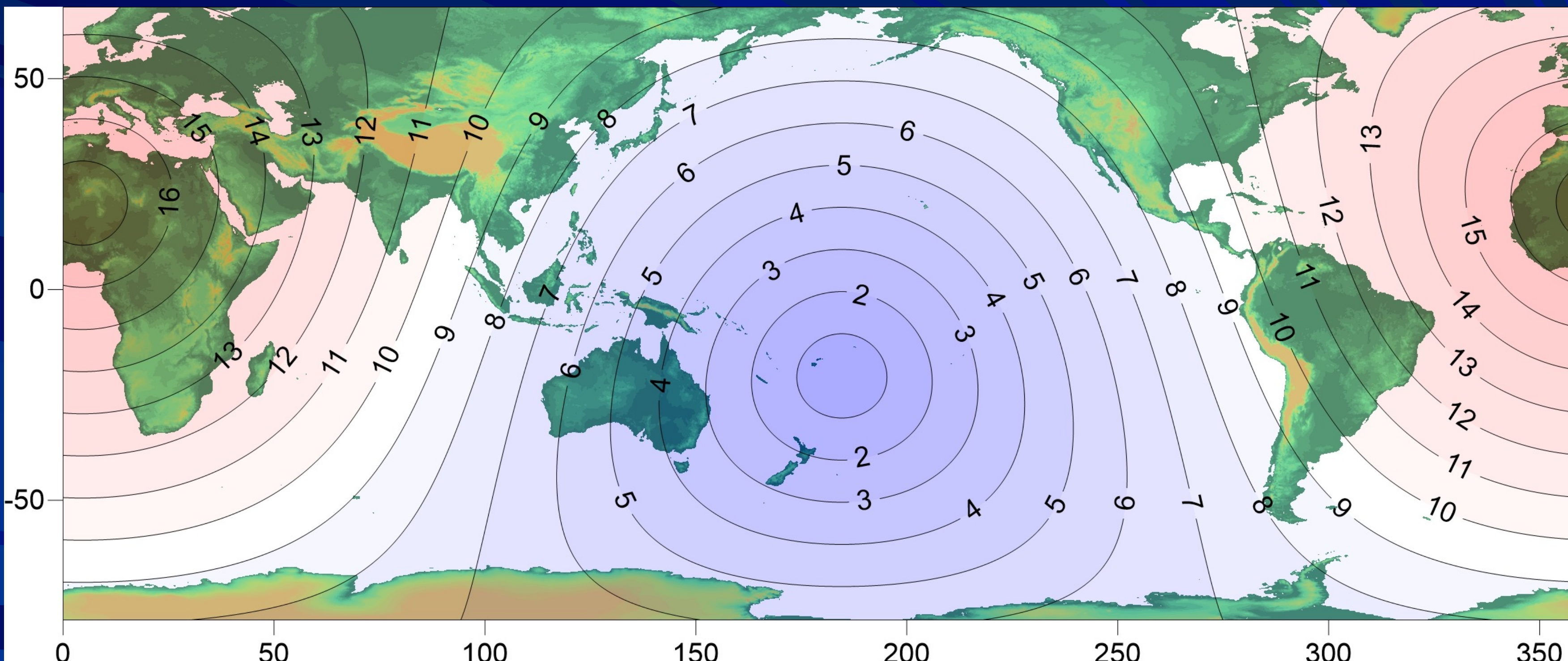
GOES-West satellite image (US NOAA) of the Tonga-Hunga volcanic eruption (05:10 UTC, Jan 15, 2022)

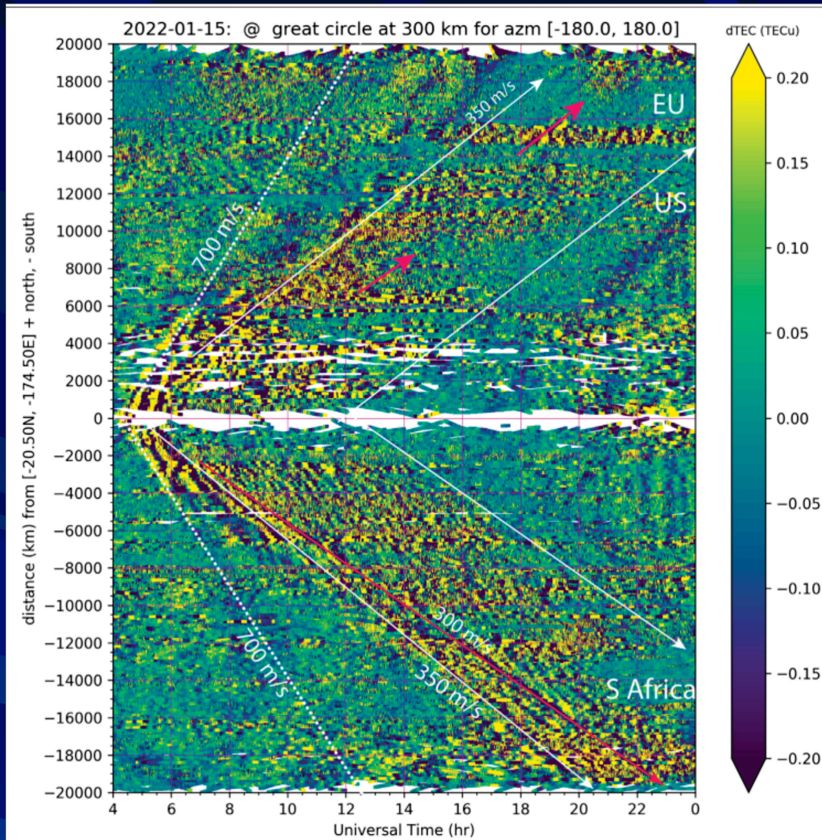
Tsunami generation at remote stations



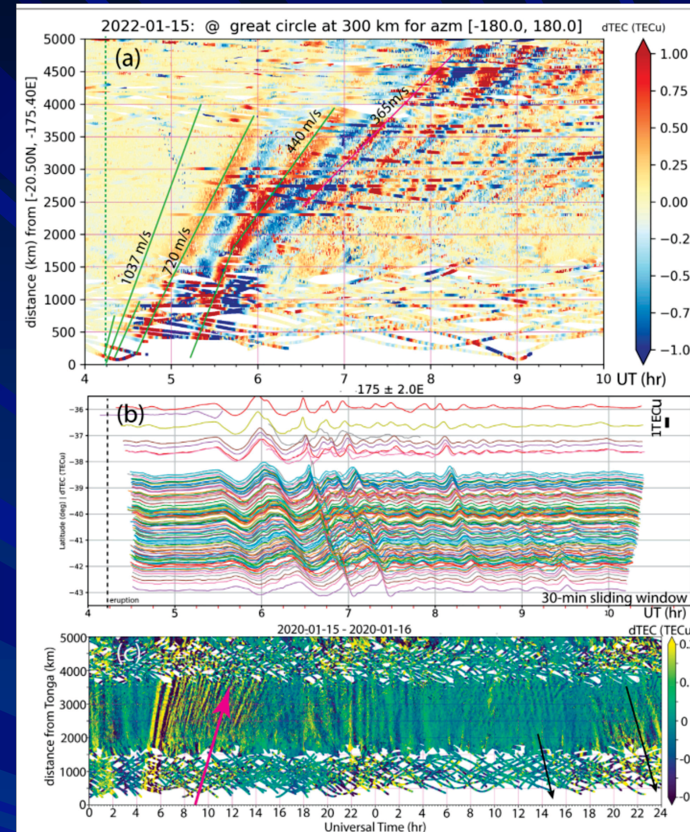
From *Monserrat, Vilibic' and Rabinovich* [2006]

Atmospheric waves



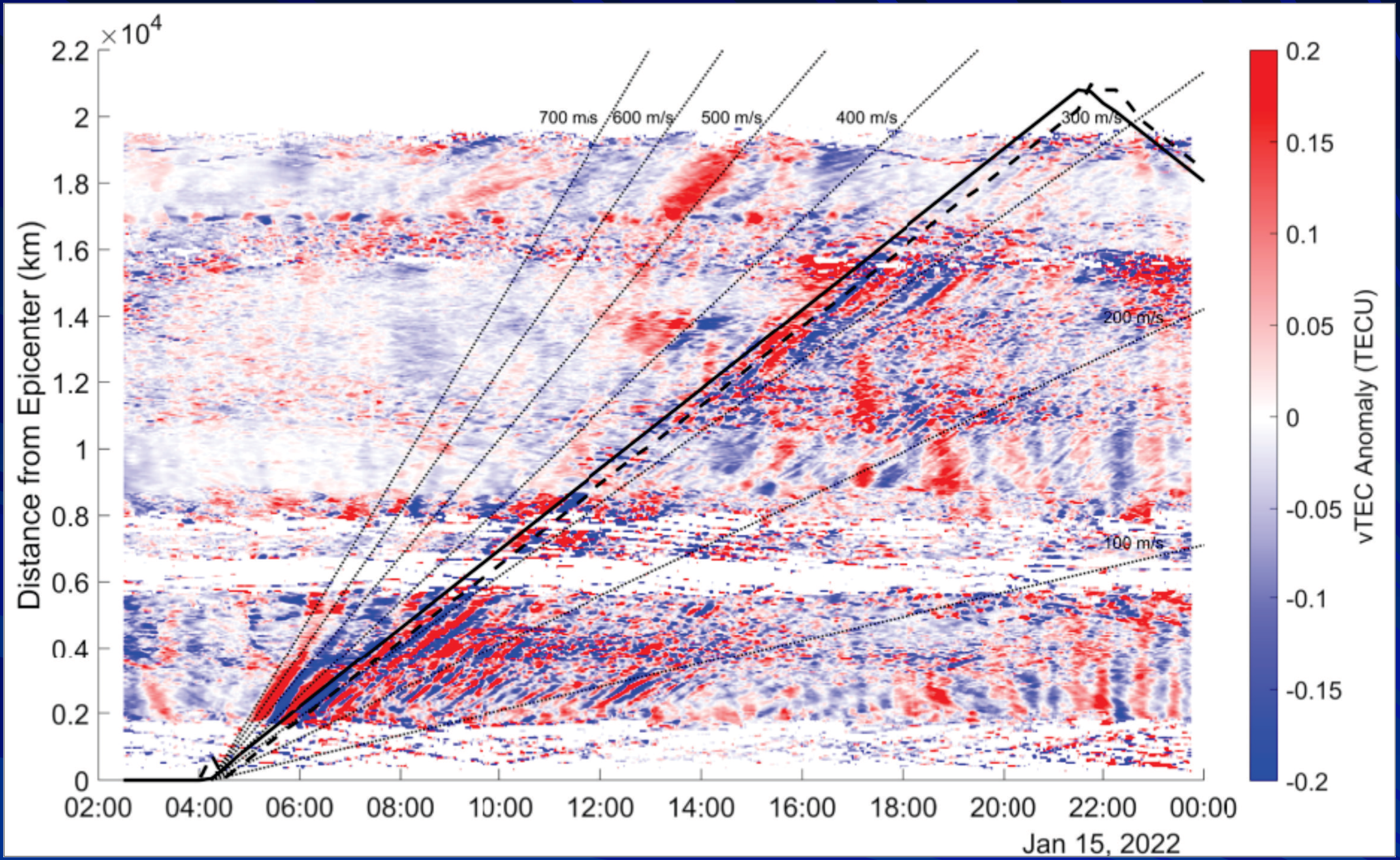


Distance-UT variation of dTEC for disturbance propagation southward (negative distance) and northward (positive distance) along the great circle paths at 300 km altitude on 15 January. White arrows provide envelope lines encompassing the ionospheric disturbances. The slopes of these lines are ~350 m/s. Dashed lines with larger slopes (~700 m/s) follow the initial ionospheric shocks which terminated after 5,000–6,000 km.



Near-field observations of initial and subsequent GNSS TEC fluctuations: (A) the distance-time variation within 5,000 km 6 h following the eruption; (B) regional GNSS TEC fluctuations in NZ showing their evolution in space and time; (C) near-field TIDs, the same as (A) but over 48 h with red arrows marking the outbound ~350 m/s wave propagation, and black arrows marking the potential returning waves at ~350 m/s into Tonga after 15:00 UTC on the following day 16 Jan.

From *Zhang et al.* [2022]



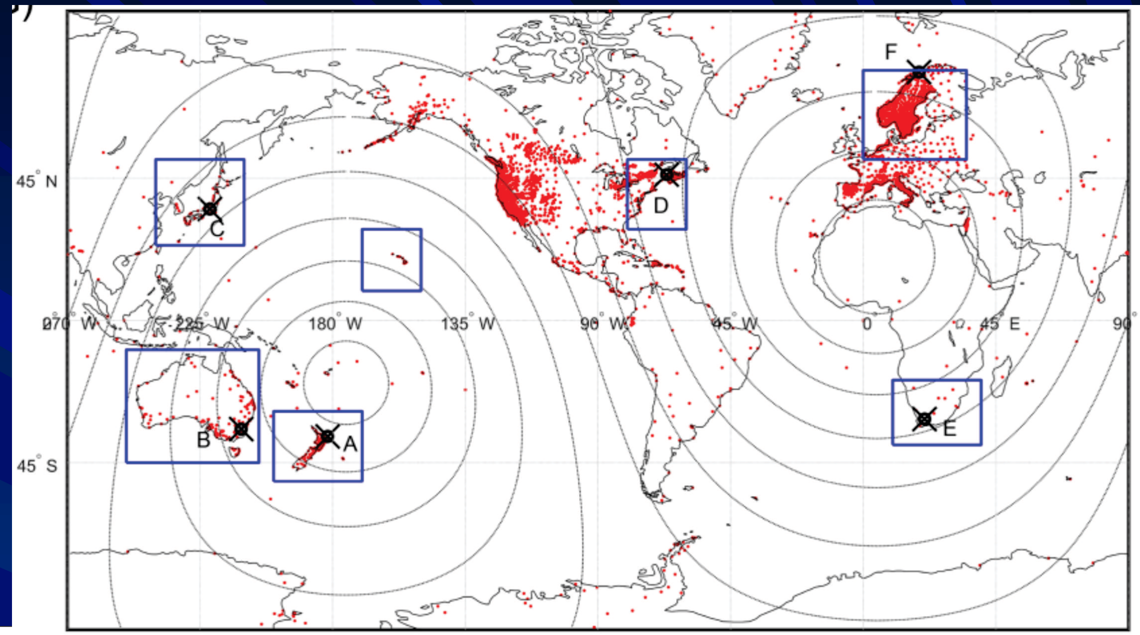
Vertical TEC anomaly averaged in 50 km bins of radial distance from the Tonga eruption epicenter. The TIGAR-modeled height anomaly peak and depression are plotted in solid and dashed black lines. Dotted black lines correspond to trajectories for fixed radial speeds from 100 to 700 m/s in increments of 100 m/s.

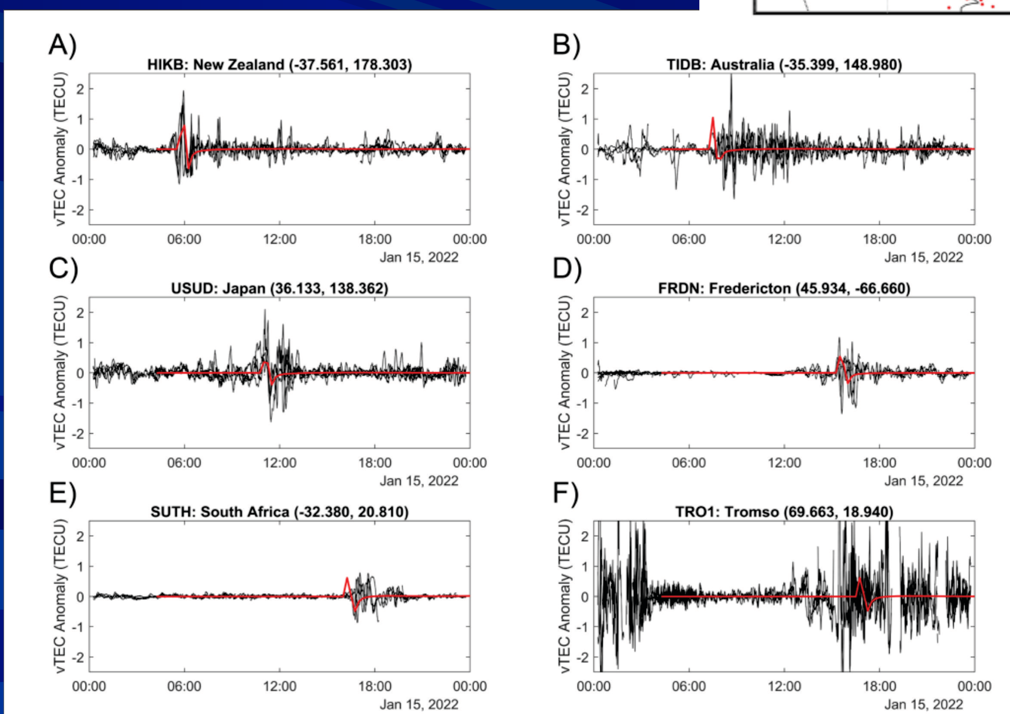
TEC = Total Electronic Content

From *Themens et al.* [2022]

Map of Global Navigation Satellite System (GNSS) receiver stations

TEC = Total Electronic Content



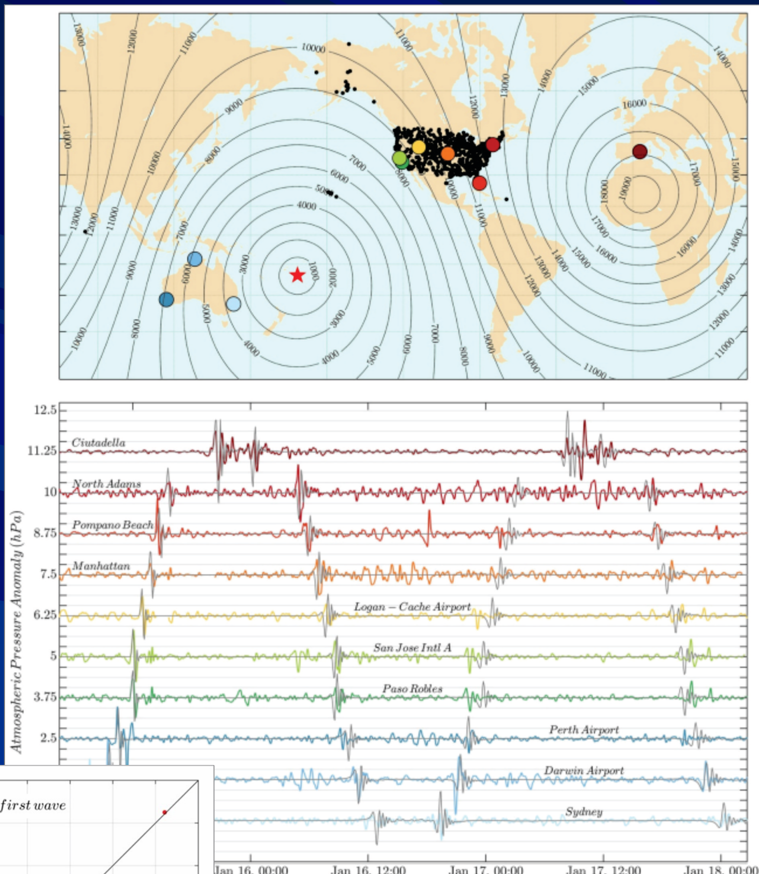


Observed (black) and TIGAR numerically modelled (red) height anomalies (in cm) for six regions

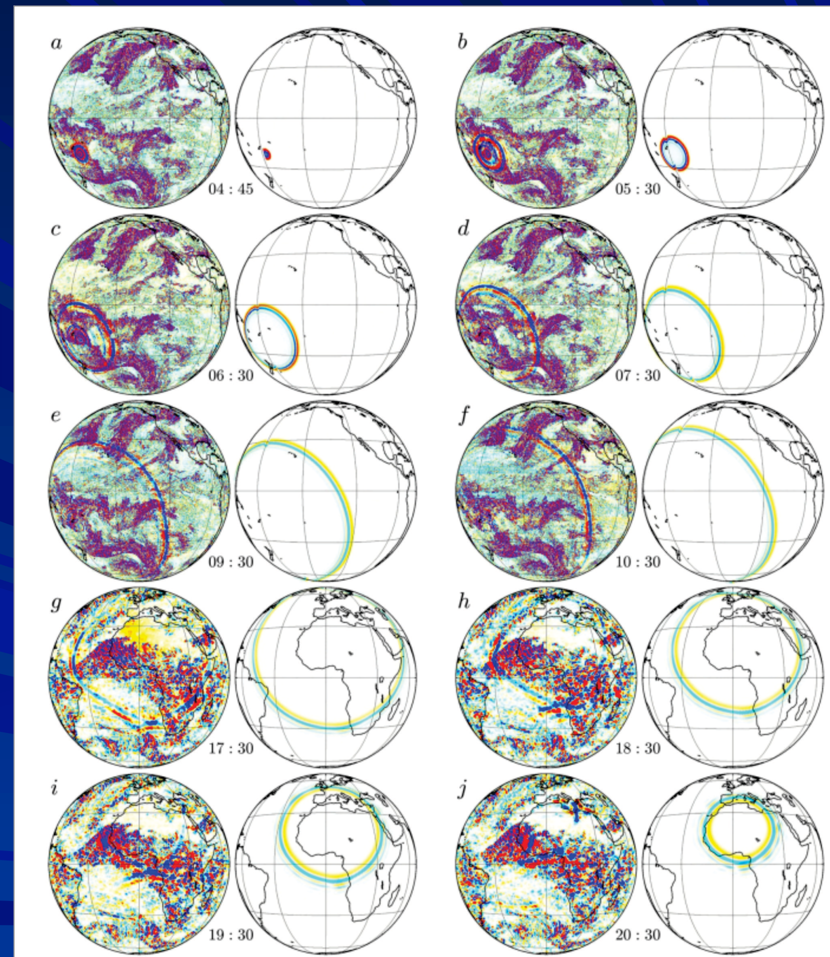
TIGAR = Transient Inertia Gravity and Rossby wave dynamics

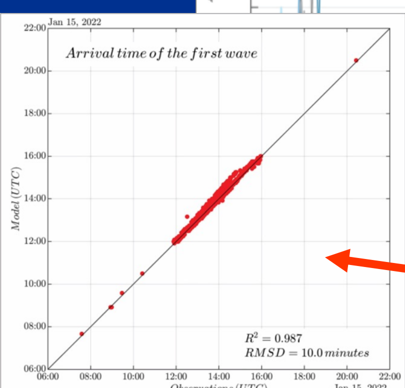
From *Themens et al.* [2022]

The location of air pressure stations and comparison of observed (coloured) and numerically simulated (black) air pressure records for the period from Jan 15, 04:30 - Jan 18, 02:40 UTC



Comparison of the satellite observed and numerically simulated Lamb wave at various times of January 15, 2020

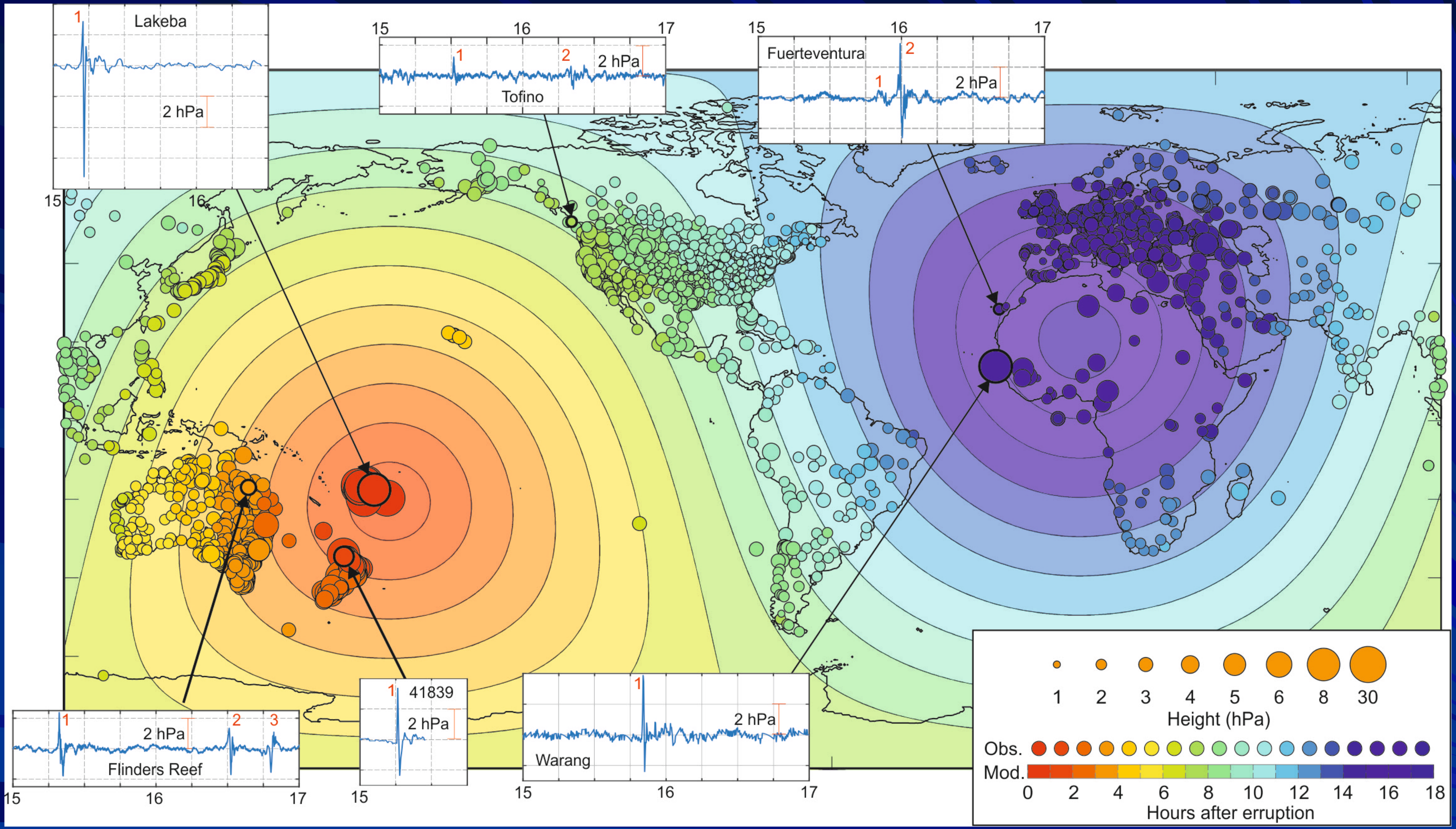




Correlation between the modeled and observed arrival times of the first eruption-induced Lamb wave

From *Amores et al.* [2022]

Tonga 2022 air pressure waves recorded around the globe



Constructed by Jadranka Šepić (**>3000 records**)

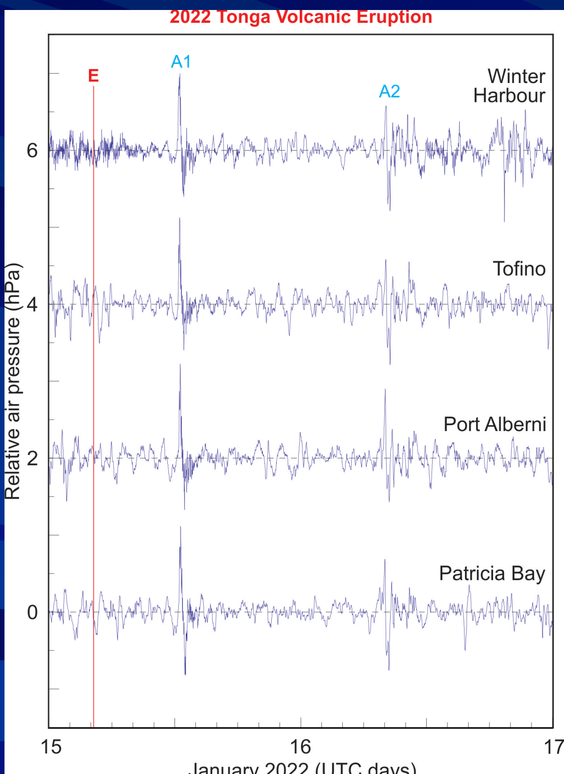
From *Joint team* [2022] (Isaac Fine, Jadranka Šepić, Igor Medvedev, Richard Thomson and Alexander Rabinovich)

Tonga 2022 air pressure waves recorded around the globe

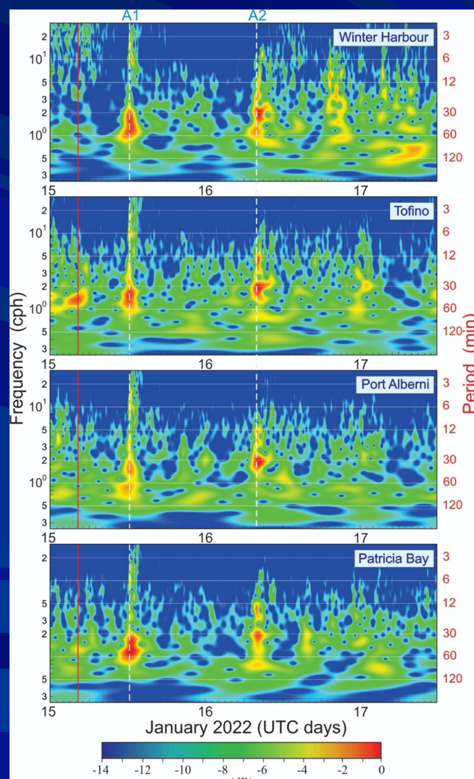
Pacific coast of Mexico

Vancouver Island, British Columbia

A1 B1 A1 B1 A2

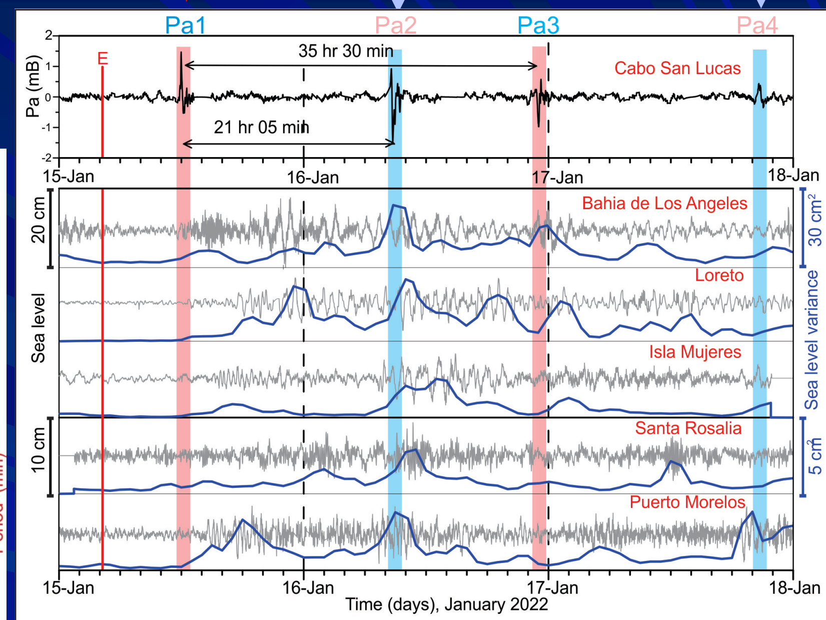


AP records



Frequency-time plots

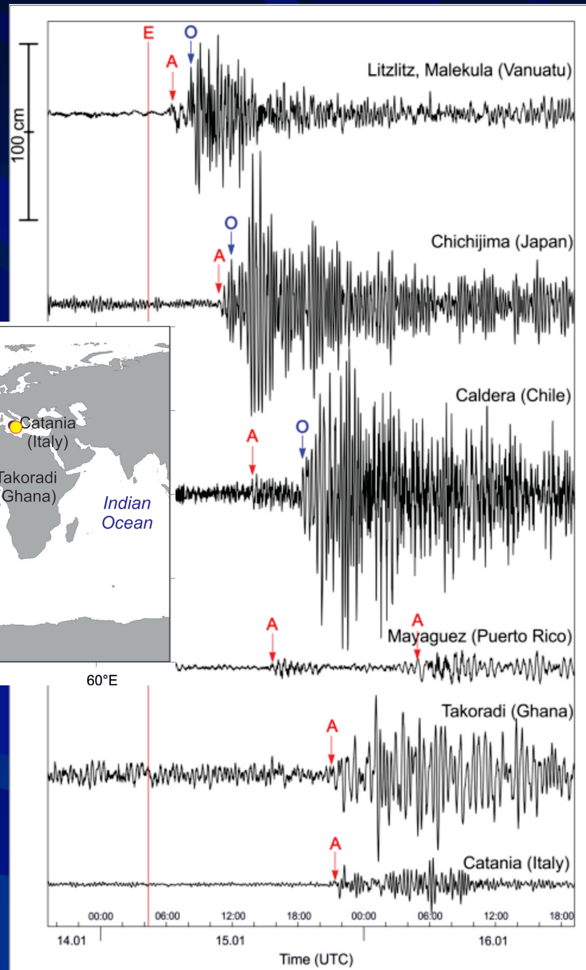
A1 B1 A2 B2

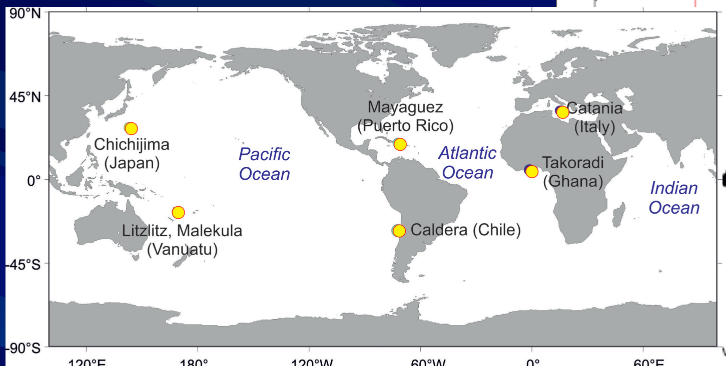


AP and SL records
(from Zaytsev et al., 2022)

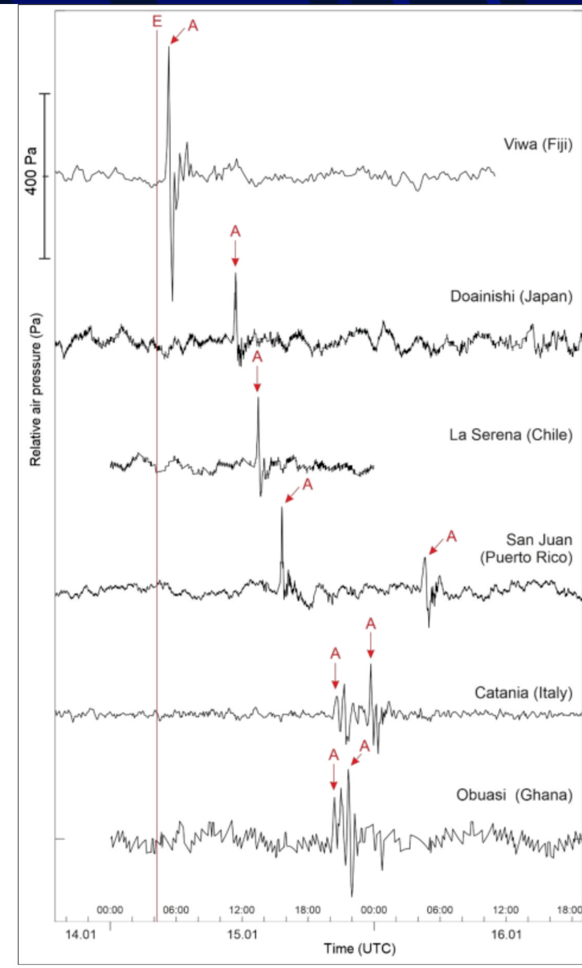
A2 – A1 = B2 – B1 ~ 35.5 hrs
Mean speed of ~313 m/s

Sea level





Air pressure



Constructed by Igor Medvedev and Jadranka Šepić

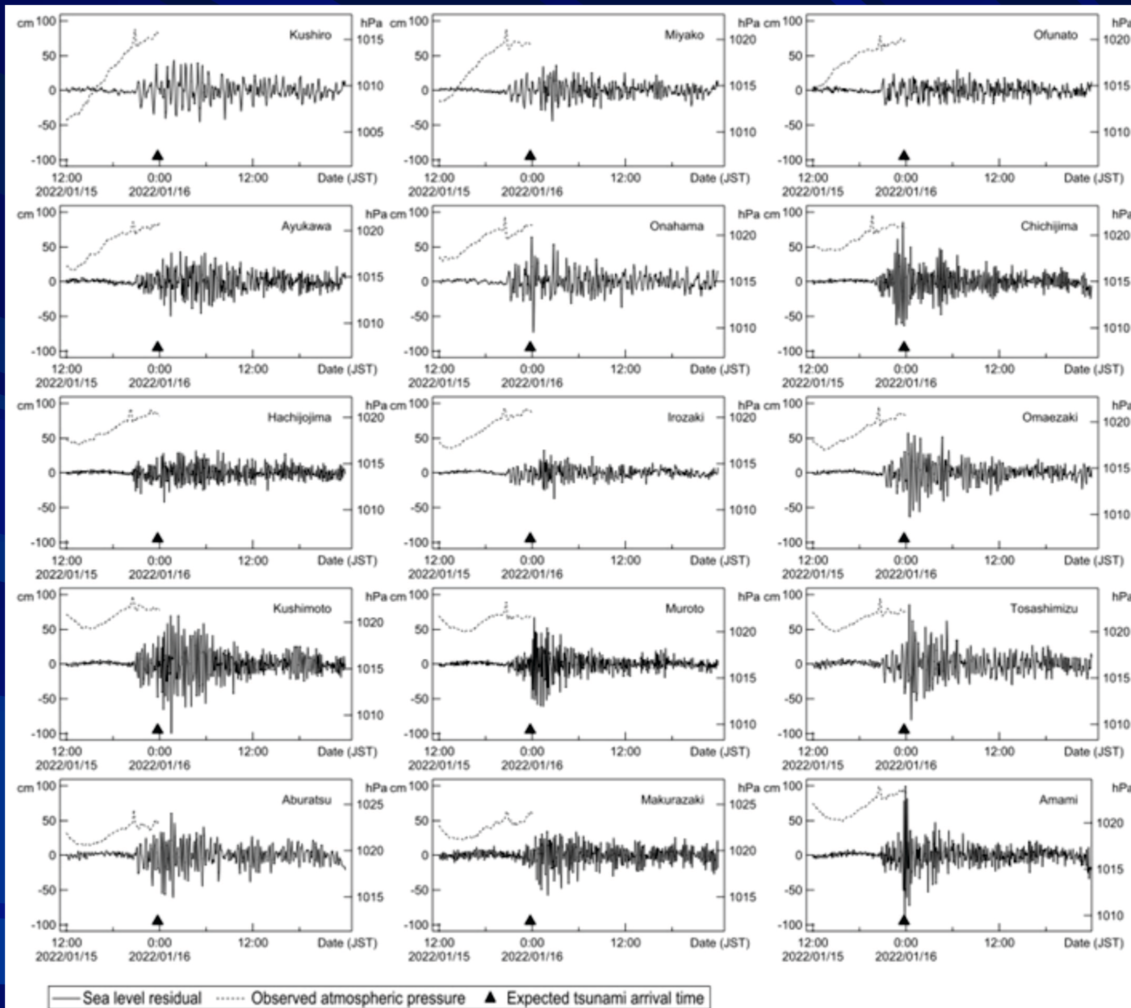
HF eruption-induced sea level oscillations at various sites around the globe. The vertical red line labelled "E" denotes the volcanic eruption; "A" indicates the arrival time of the tsunami waves caused by the atmospheric Lamb wave; "O" indicates the arrival time of the long ocean waves directly generated by the Tonga eruption on January 15, 2022.

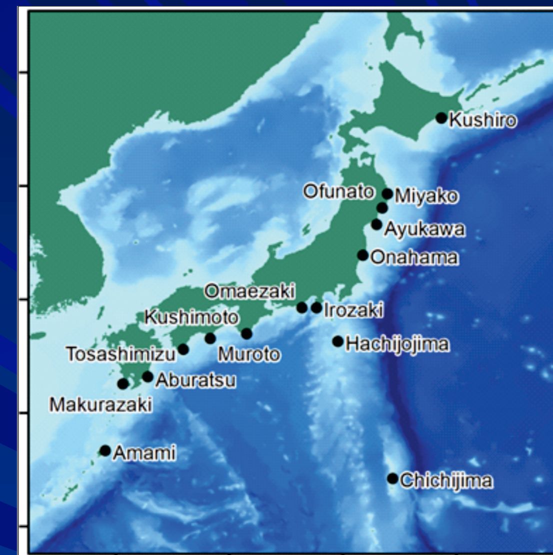
Records of relative HF air pressure fluctuations in various sites, roughly corresponding to locations of sea-level observations. The vertical red line labelled "E" denotes the volcanic eruption, "A" indicates arrival time of the atmospheric Lamb wave. The data sources are listed below

From *Kulichkov et al.* [2022]

Tsunami waves

Air pressure and sea level Tonga-induced oscillations on the Pacific coast of Japan

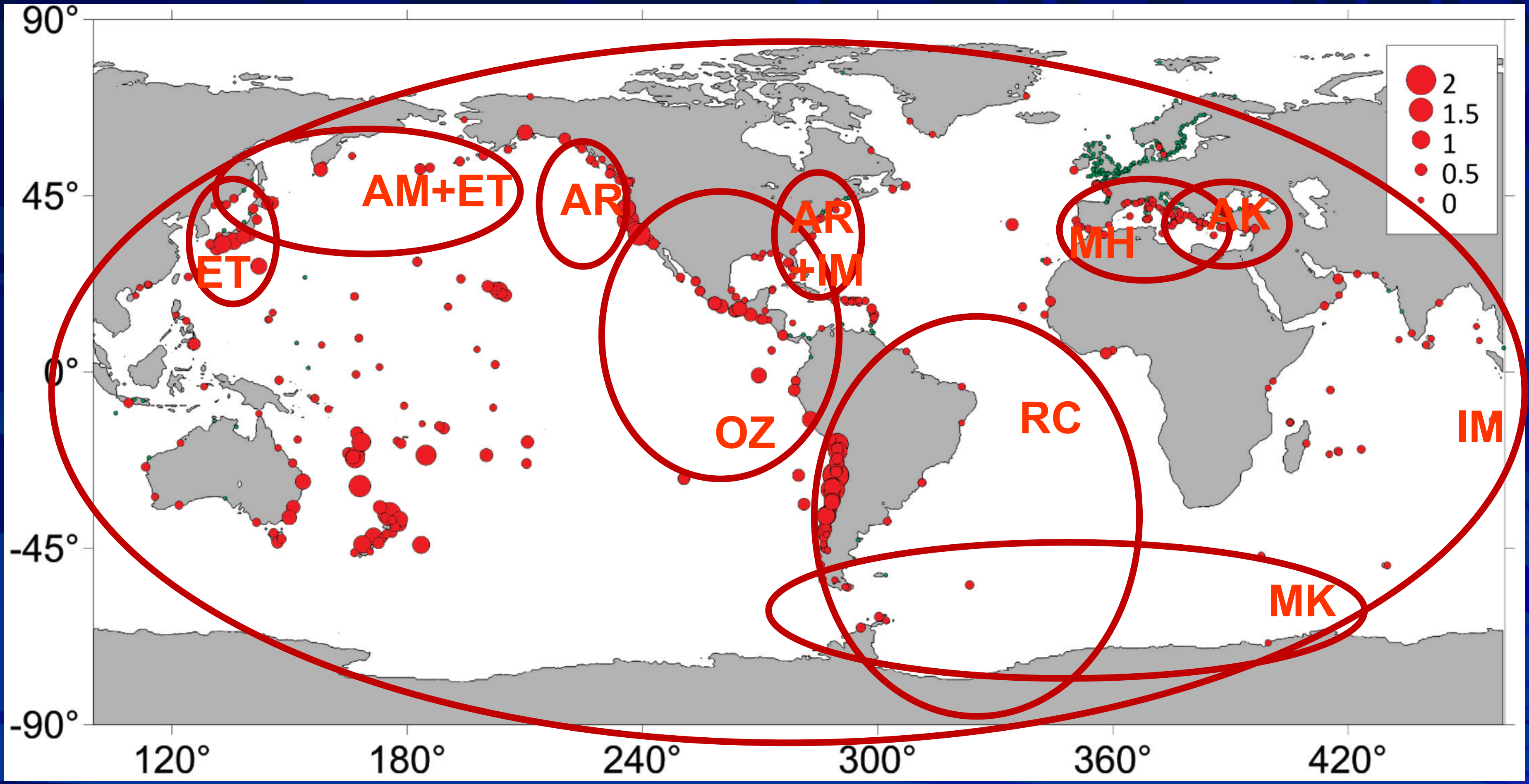




From *Imamura et al.* [2022]

The tsunami caused by the Tonga submarine volcanic eruption that occurred at 13:15 Japan Time 16 (JST) on January 15, 2022, exposed a blind spot in Japan's tsunami monitoring and warning system, which was established in 1952 for local tsunamis and expanded to distant tsunamis after the 1960 Chile tsunami.

Recorded 2022 Tonga tsunami waves around the globe



AK = Arina Korzhenovskaya
AM = Alisa Medvedeva
AR = Alexander Rabinovich

ET = Elizaveta Tsukanova
IM = Igor Medvedev
MH = Mohammad Heidarzadeh

MK = Mikhail Kulikov
OZ = Oleg Zaytsev
RC = Rogerio Candella

Tsukanova, E. and Medvedev, I. (2022) The observations of the 2022 Tonga-Hunga tsunami in the Sea of Japan, *Pure and Applied Geophysics,* 179, 4279-4299

Pure Appl. Geophys. 179 (2022), 4279–4299

https://doi.org/10.1007/s00024-022-03191-w

Pure and Applied Geophysics

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The Observations of the 2022 Tonga-Hunga Tsunami Waves in the Sea of Japan

Elizaveta Tsukanova[1] and Igor Medvedev[1]

Abstract—On 15 January 2022, the Tonga-Hunga submarine volcano erupted in the southwest Pacific Ocean and created strong tsunami waves that had a dual generation mechanism: "direct" (caused by the explosion) and "atmospheric" (induced by propagating atmospheric Lamb waves). Trans-oceanic waves spread across the ocean and were clearly recorded in marginal seas of the northwestern Pacific, including the Sea of Japan. The two distinct types of incoming waves produced a variety of effects in the sea as determined by the wave origin, propagation features and local topographic properties. Statistical and spectral properties of the tsunami waves recorded in the Sea of Japan and vicinity, including the adjacent part of the northwestern Pacific, are the main subject of the present study. The Sea of Japan is a semi-isolated basin connected to the Pacific Ocean through several straits. The features of these straits (widths, depths, and geometry) significantly affected the arriving waves, strongly modifying their statistical characteristics and spectral content. As discussed in detail in this paper, the two types of incoming tsunami waves are consequently transformed in substantially different ways.

Keywords: tsunami, Tonga-Hunga Volcano, Sea of Japan, tide gauges, Lamb wave, air pressure, meteotsunami, eruption, straits.

1. *Introduction*

According to the report of the Tonga National Emergency Management Office (NEMO), the Kingdom of Tonga, on 20 December 2021, volcanic activity of the Tonga-Hunga Volcano was recorded (ash was found in the air) and air traffic from Tonga was suspended. The monitoring continued until 2 January and on 11 January it was announced that there was no volcanic activity after 2 January. But on 14 January, the alarm was renewed due to the strong smell of sulphur. Then, on 15 January at 4:15 UTC a strong volcanic eruption occurred (20.54°S; 175.39°W) (USGS, 2022).

The volcanic eruption generated tsunami waves. In the near-field zone (near the Tongatapu Islands, 'Eua, and the Ha'apai Islands), their height reached 15 m (Omira et al., 2022). As a result of the event, the undersea communications cable was damaged in several places (ETC Situation Report, 2022), which, combined with the giant ash cloud emitted into the atmosphere, led to the termination of communications with Tonga. In addition, the rapid updraft of hot gases and ash from the erupting volcano led to the formation of atmospheric Lamb waves (Adam, 2022; Duncombe, 2022). These waves were recorded at many sites along the Pacific coast, including the Kamchatka Peninsula and Aleutian Islands (Imamura et al., 2022; Kubota et al., 2022).

The eruption of the Tonga volcano created two types of tsunami waves: (1) atmospherically induced and (2) "direct" oceanic gravity waves (cf. Amores et al., 2022). The gravity tsunami waves formed in the area of the volcanic eruption propagated across the Pacific Ocean at the speed of long waves:

$$c = \sqrt{gH}, \quad (1)$$

where $g = 9.81$ m/s^2 is the gravity acceleration and H is the ocean depth (m).

The eruption of the Tonga volcano also generated acoustic-gravity Lamb waves (Amores et al., 2022; Kulichkov et al., 2022) that propagated around the Earth at a speed of

$$u = \sqrt{\frac{\gamma RT}{\mu}}, \quad (2)$$

where $\gamma = 1.4$ is the ratio of specific air heats corresponding to the range of atmospheric temperatures, $R = 8.31$ J/mol·K is the universal gas constant,

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◄Figure 9
a Map of the locations of the tide gauges; **b** sea level records at eight stations in the Sea of Japan for the period of 15–16 January 2022. The solid vertical red line labelled "E" indicates the time of the eruption; red band is the arrival time of the atmospheric wave (A), green band is the arrival time of the ocean tsunami wave through the Korea Strait (KS), orange band through the Tsugaru Strait (TS), magenta band through La Perouse Strait (LPS); **c** *f–t* diagrams of the sea level records in Rudnaya Pristan, Preobrazheniye, and Vladivostok

the tsunami waves generated (a) around the volcano source region by the seafloor crustal deformation due to eruptions, caldera collapses, and other mechanisms such as flank failures, sector collapses, and pyroclastic flows; and (b) the Lamb-wave air pressure pulse. Unfortunately, it is very difficult to separate these waves according to the records of the coastal tide gauges.

The first two types of tsunami waves penetrated into the Sea of Japan in several ways (through different straits), and as a result had different wave characteristics: amplitudes, speeds, frequency composition, etc. The straits are low-frequency filters that pass waves with long periods and prevent the penetration of high-frequency waves. In this regard, straits play the role of some filter, i.e. *response functions* transforming and modifying the input waves according to frequency admittance properties of the corresponding strait. Miles (1971) used an electric

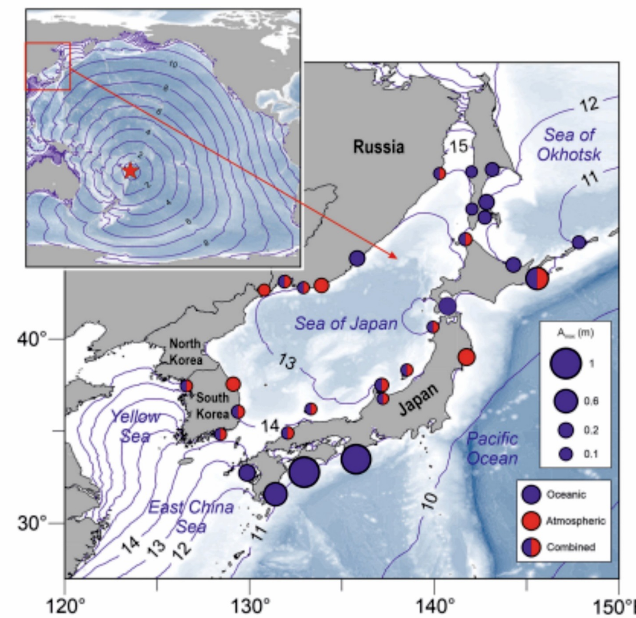


Figure 10
Map showing isochrones of the "direct" wave travel times (T_g^{travel}) in hours. The colour of the circles indicates the nature of the maximum wave and their size indicates amplitudes (A_{max})

The 2022 Tonga tsunami CHS observations on the coast of British Columbia (CHS = Canadian Hydrographic Service)

Winter Harbour – Port Alice region

Prince Rupert region

Four CHS air pressure stations

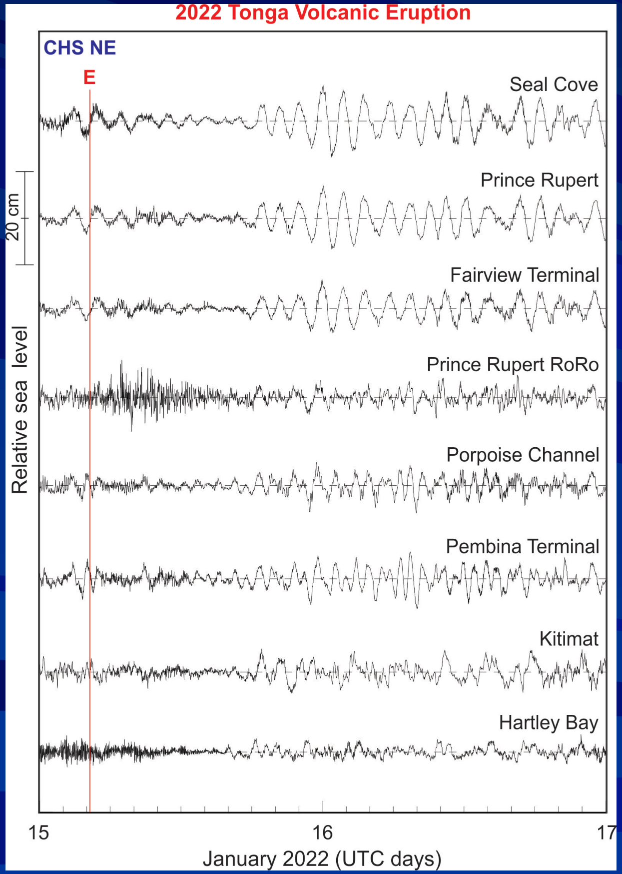
Saanich region

The 2022 Tonga tsunami was recorded at 32 tide gauge stations on the BC coast, including highly sheltered.

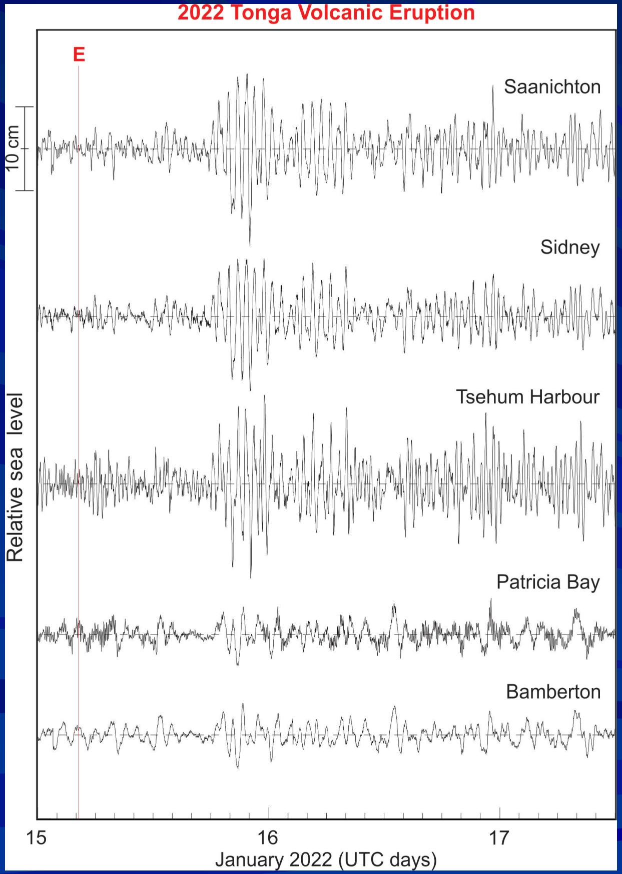
Tide gauge records of the 2022 Tonga tsunami in three sheltered regions of the BC coast

The strongest tsunami recorded at this coast, except six major (1946, 1952, 1957, 1960, 1964 and 2011)

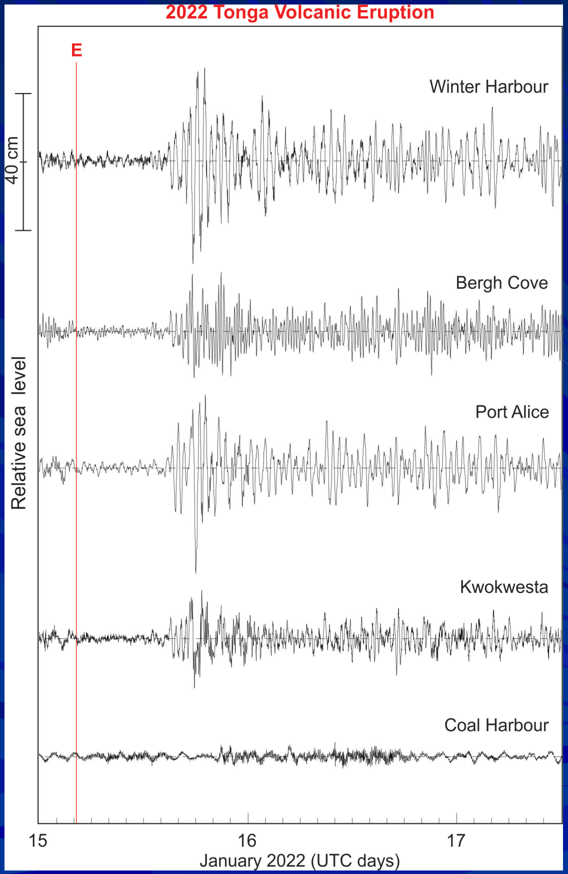
Prince Rupert region



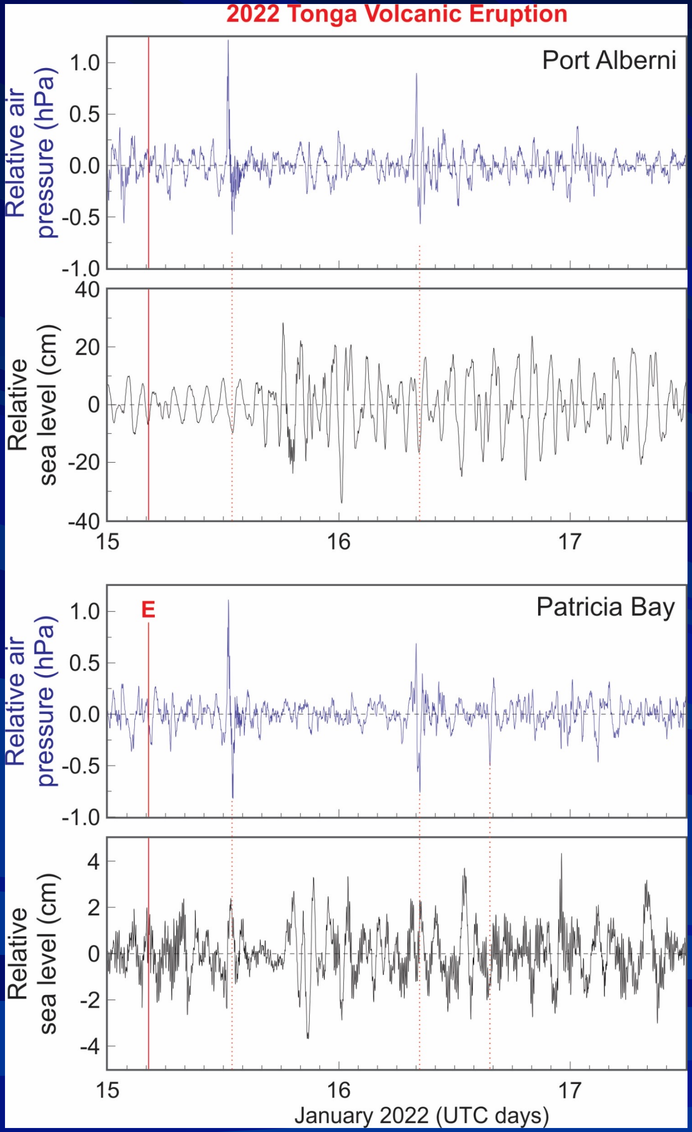
Saanich region

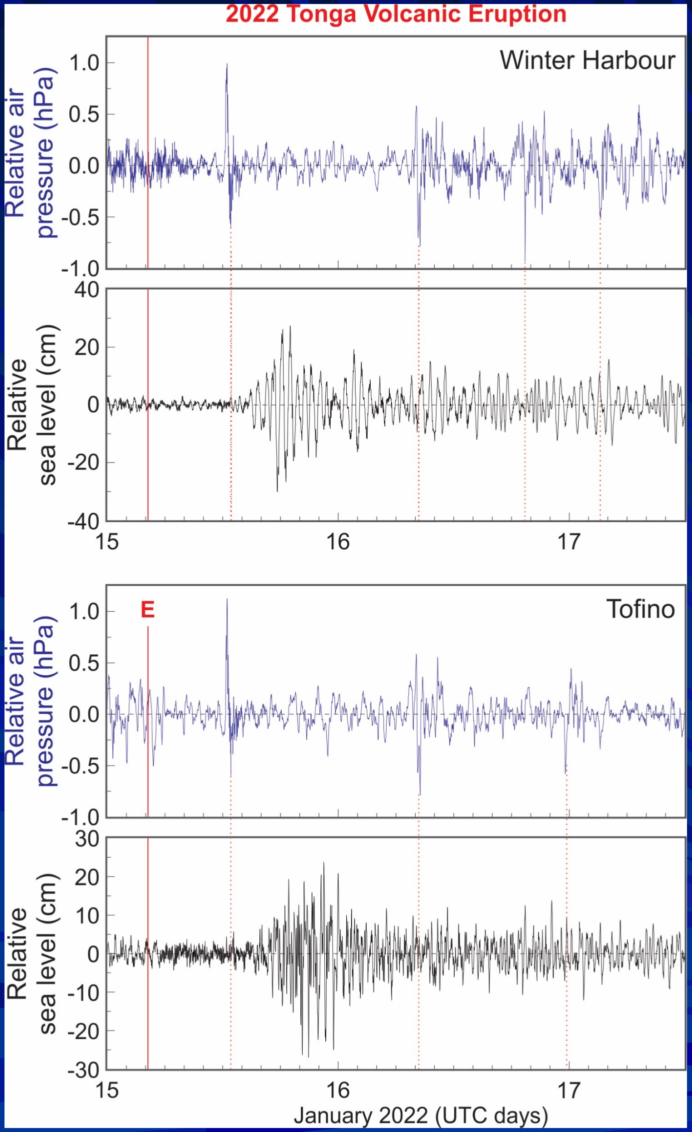


NW Vancouver Island

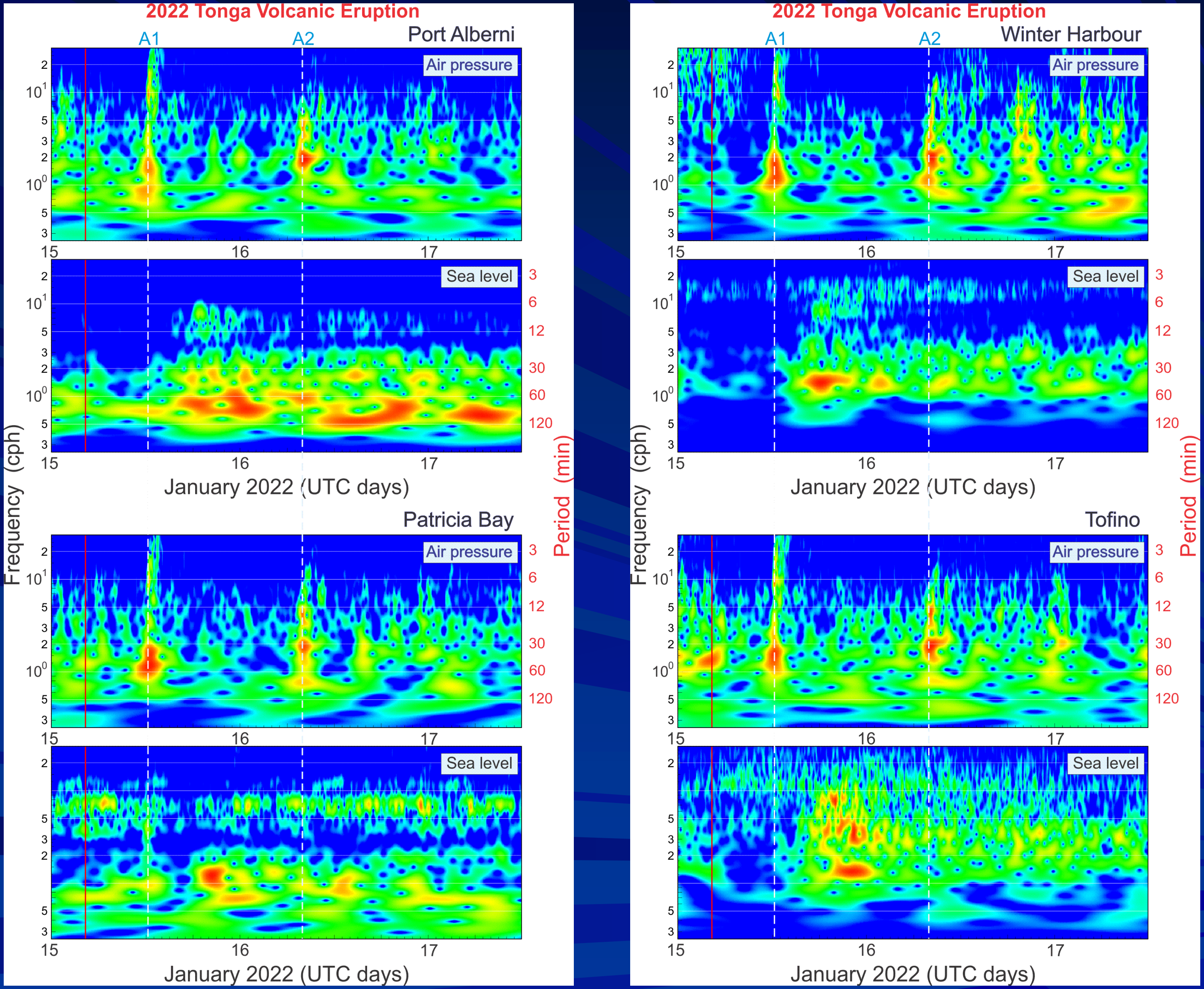


Simultaneous sea level and air pressure records



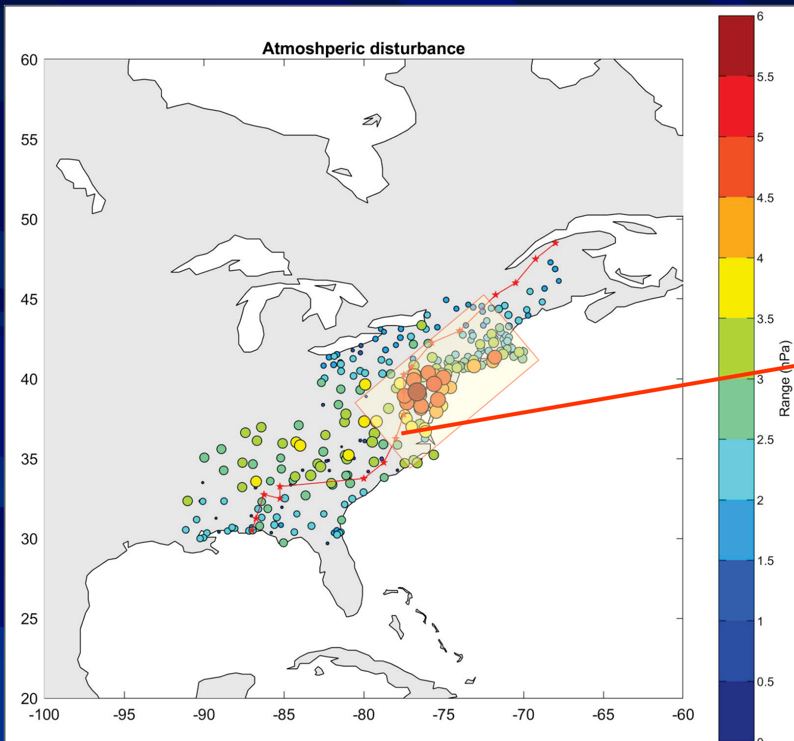


F-t plots of simultaneous sea level and air pressure records

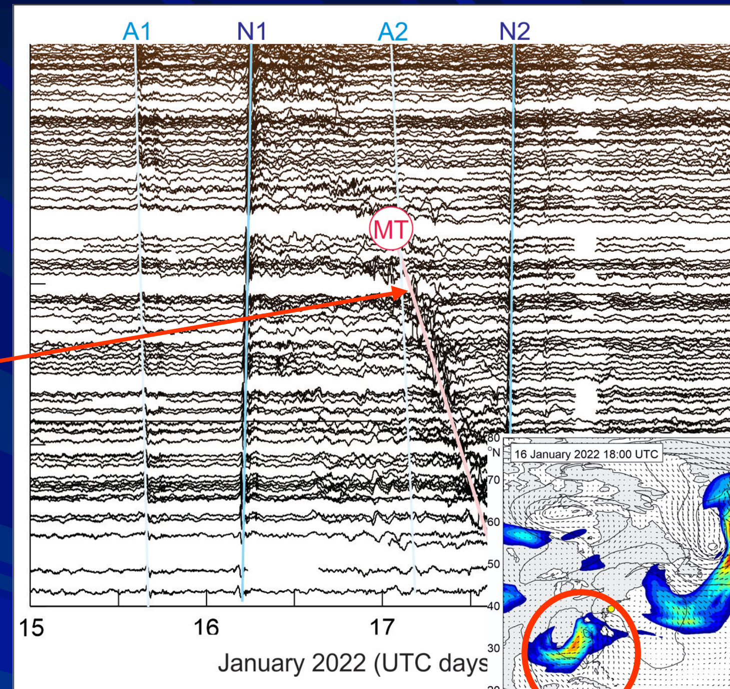


East (Atlantic) Coast

Meteorological stations

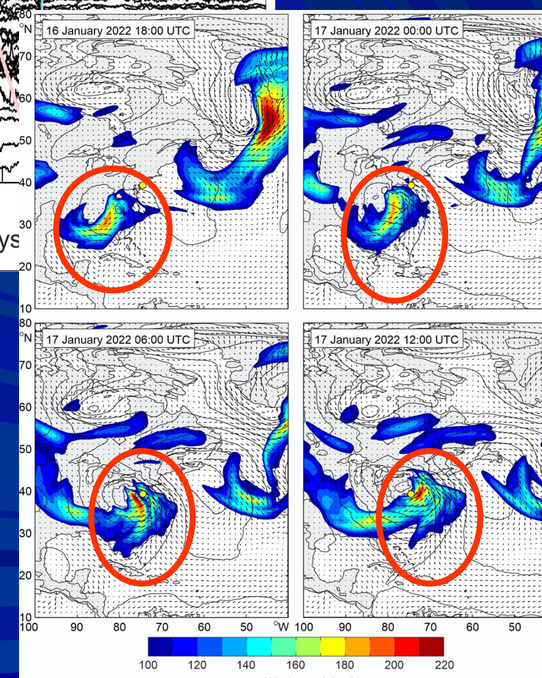


Air pressure records



South

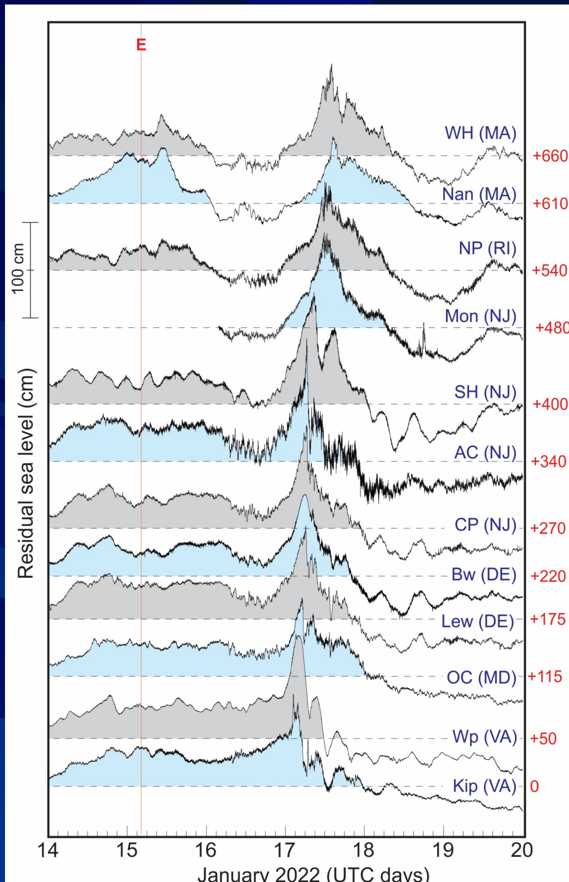
North



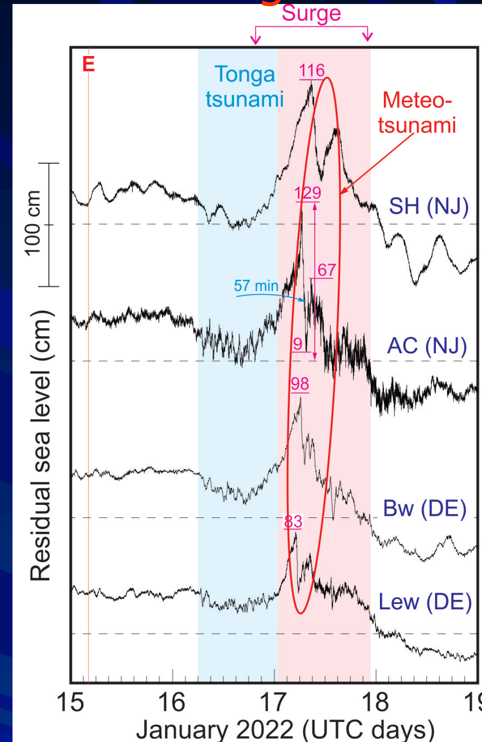
Tripple effect of the air pressure:

- Moving cyclone (LF) → *Storm surge*
- AP disturbance (HF) → *Meteotsunami*
- Tonga Lamb waves → *Tonga tsunami*

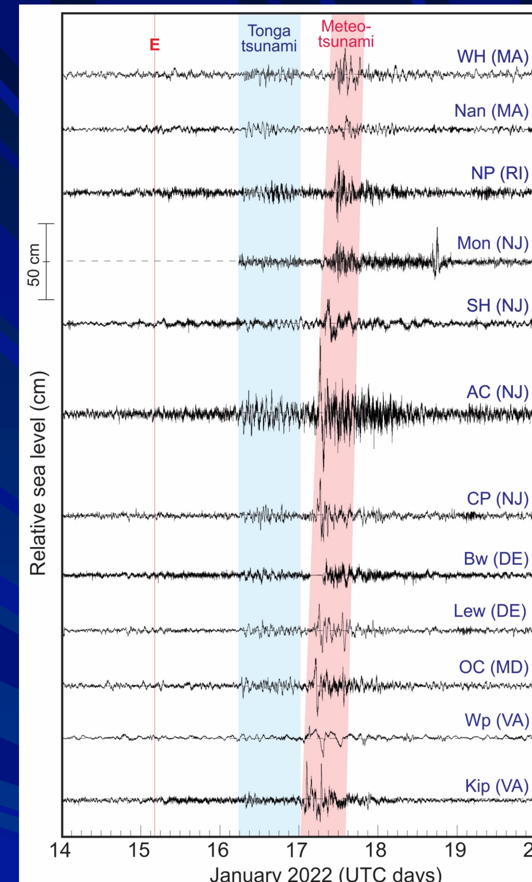
Sea level records



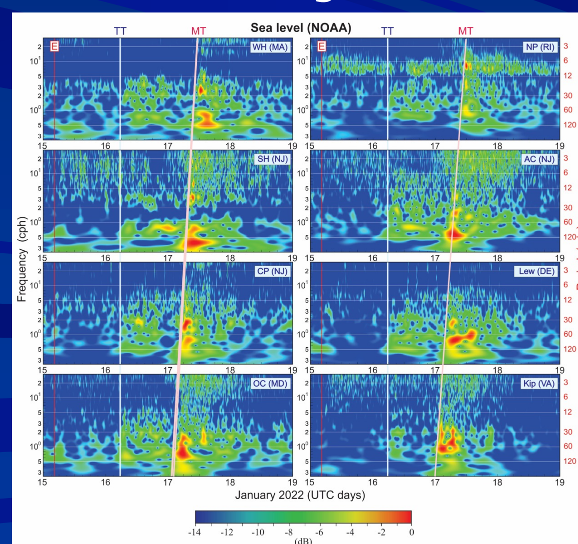
"Hot region"



HF sea level records



F-t diagrams

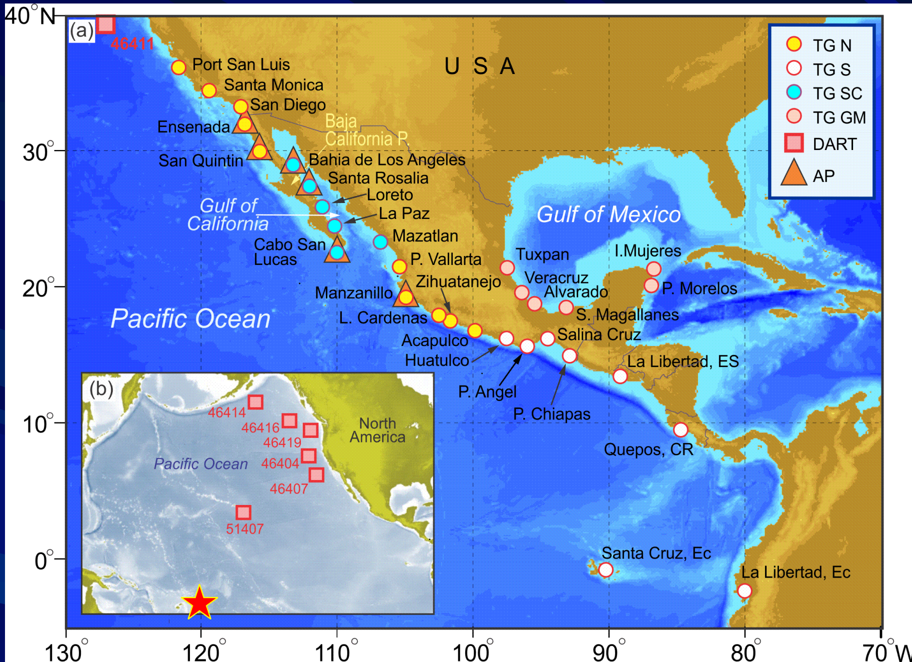


Three types of SL oscillations:

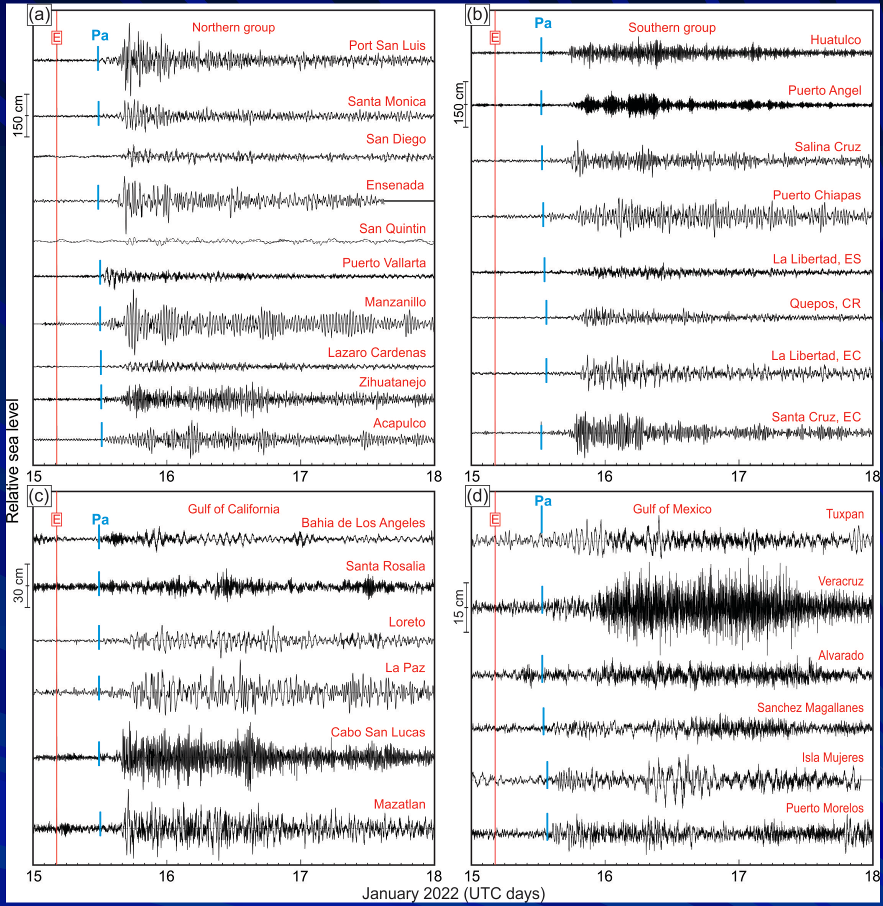
- ***Storm surge***
- ***Meteotsunami***
- ***Tonga AP tsunami***

Tipple effect: Three in one!

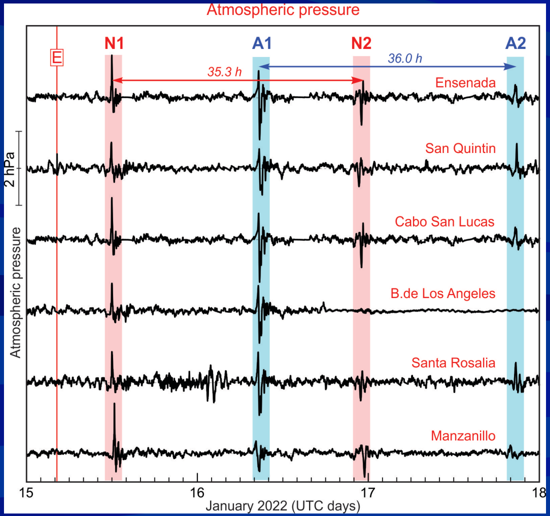
Mexican coast



Sea level records



Air pressure records

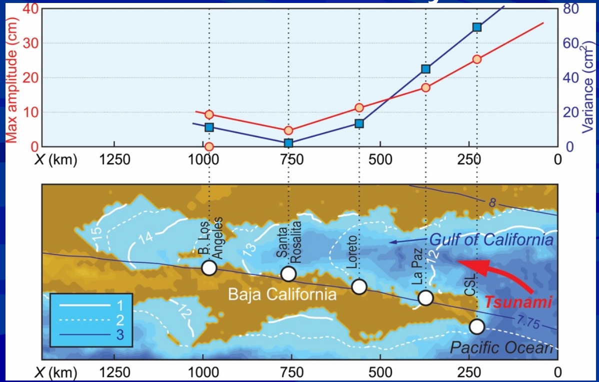


A2 – A1 = N2 – N1 ~ 35.5 hrs

Mean speed of ~313 m/s

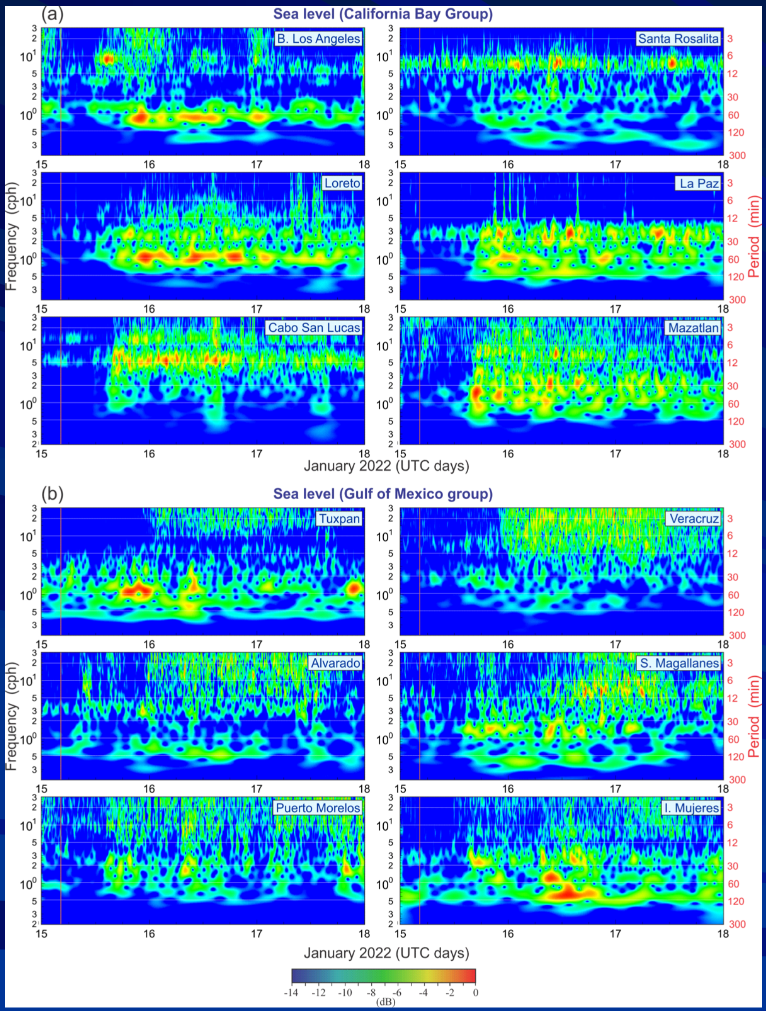
(from Zaytsev et al., 2023)

California Bay

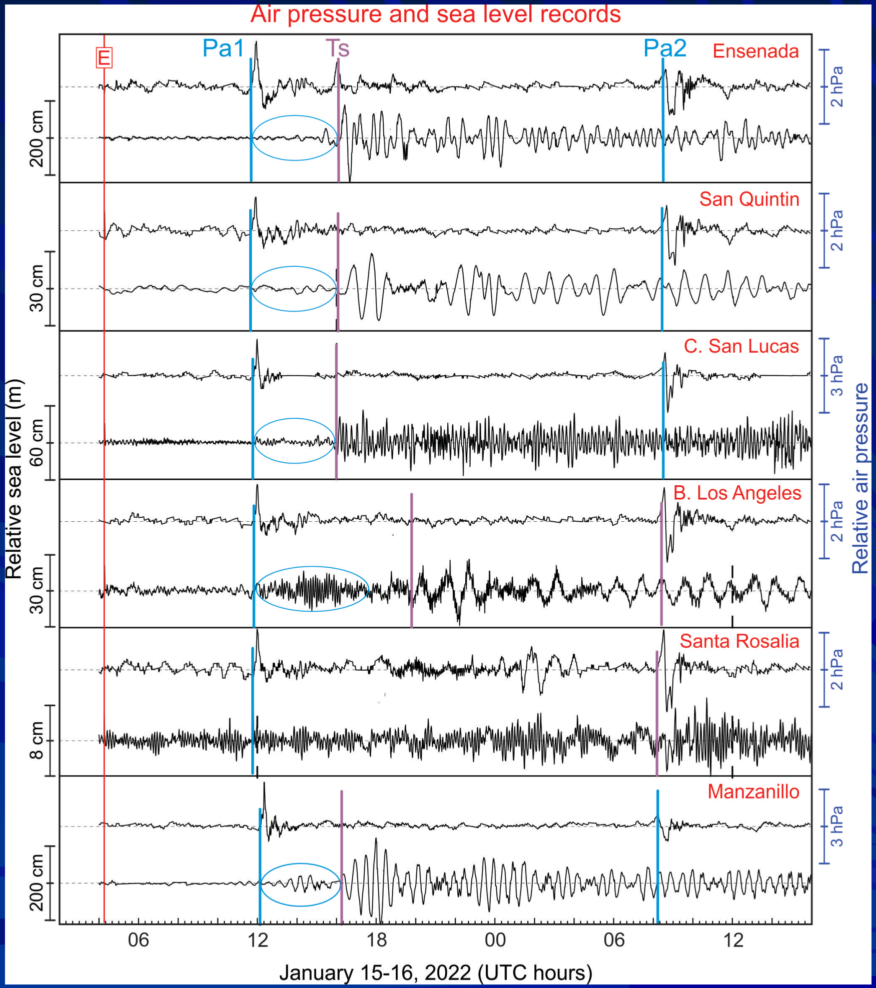


Analyses of tide gauge records on the Mexican coast

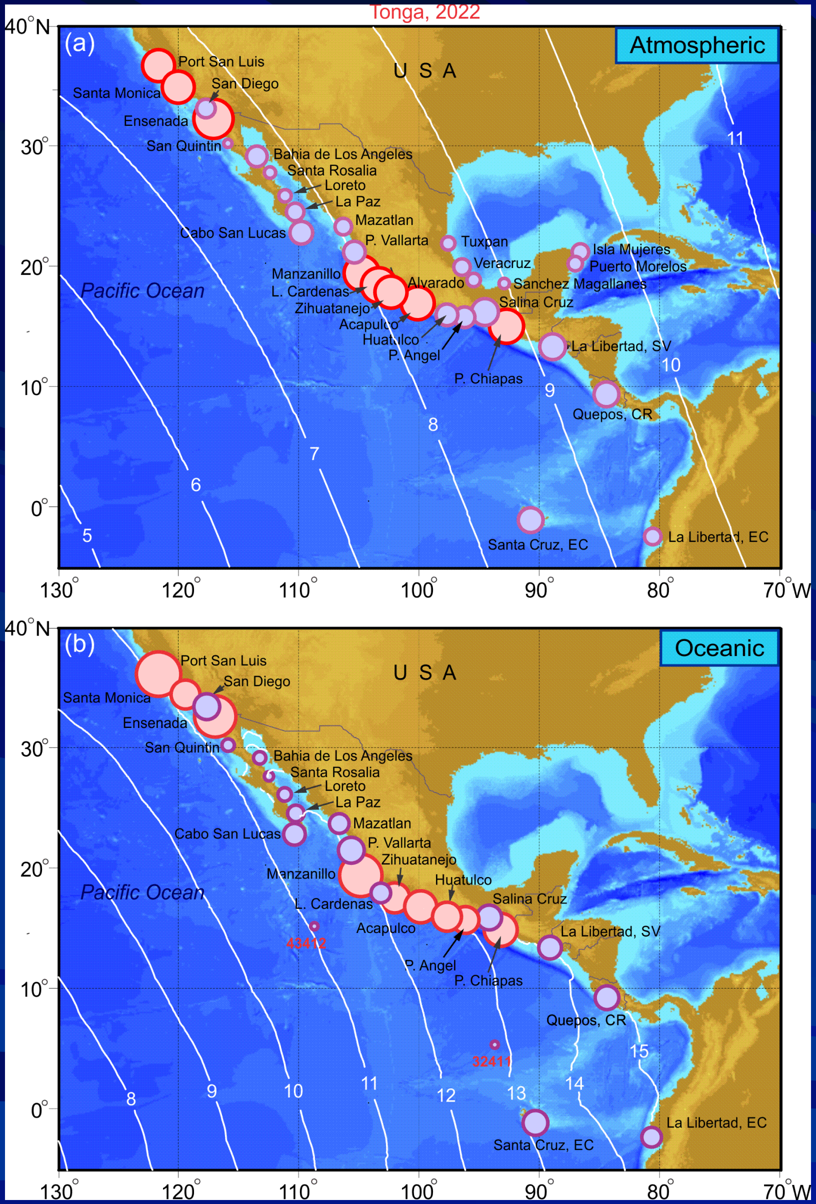
F-t (wavelet) diagrams



AP and SL records on the Pacific coast



(from Zaytsev et al., 2023)



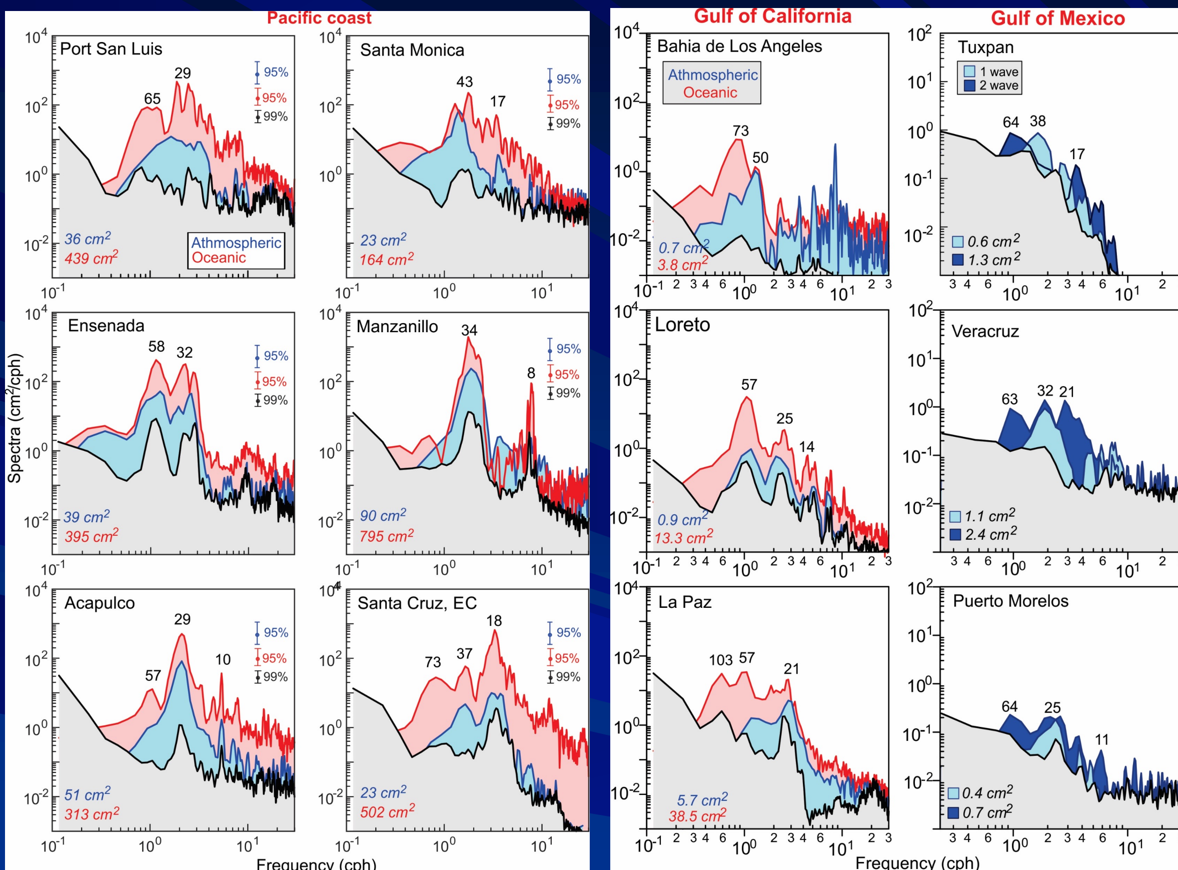
General maps of the Tonga tsunami on the coasts of USA, Mexico and Central America

Meteotsunami ⟵

Oceanic ("direct") wave ⟵

(from Zaytsev et al., 2023)

Spectral estimates



$$S_{obs}(w) = S_{bg}(w) + S_{tsu}(w)$$

$$S_{tsu}(w) = H(w) S_s(w)$$

$$S_{bg}(w) = H(w) S_0(w)$$

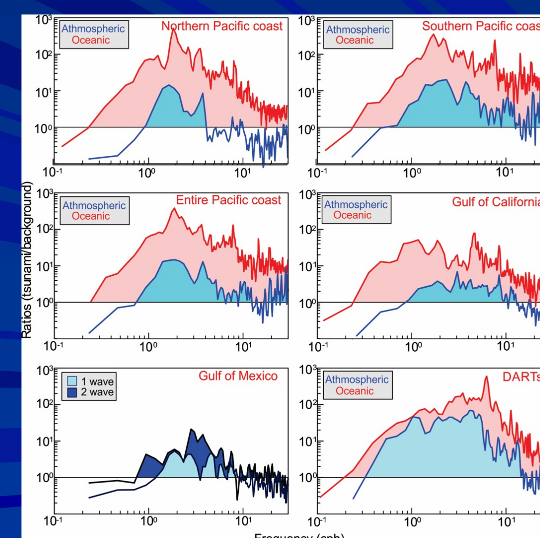
$H(w)$ = Admittance

$S_0(w)$ = Open-ocean background spectrum

Background Oceanic Atmospheric 1,2

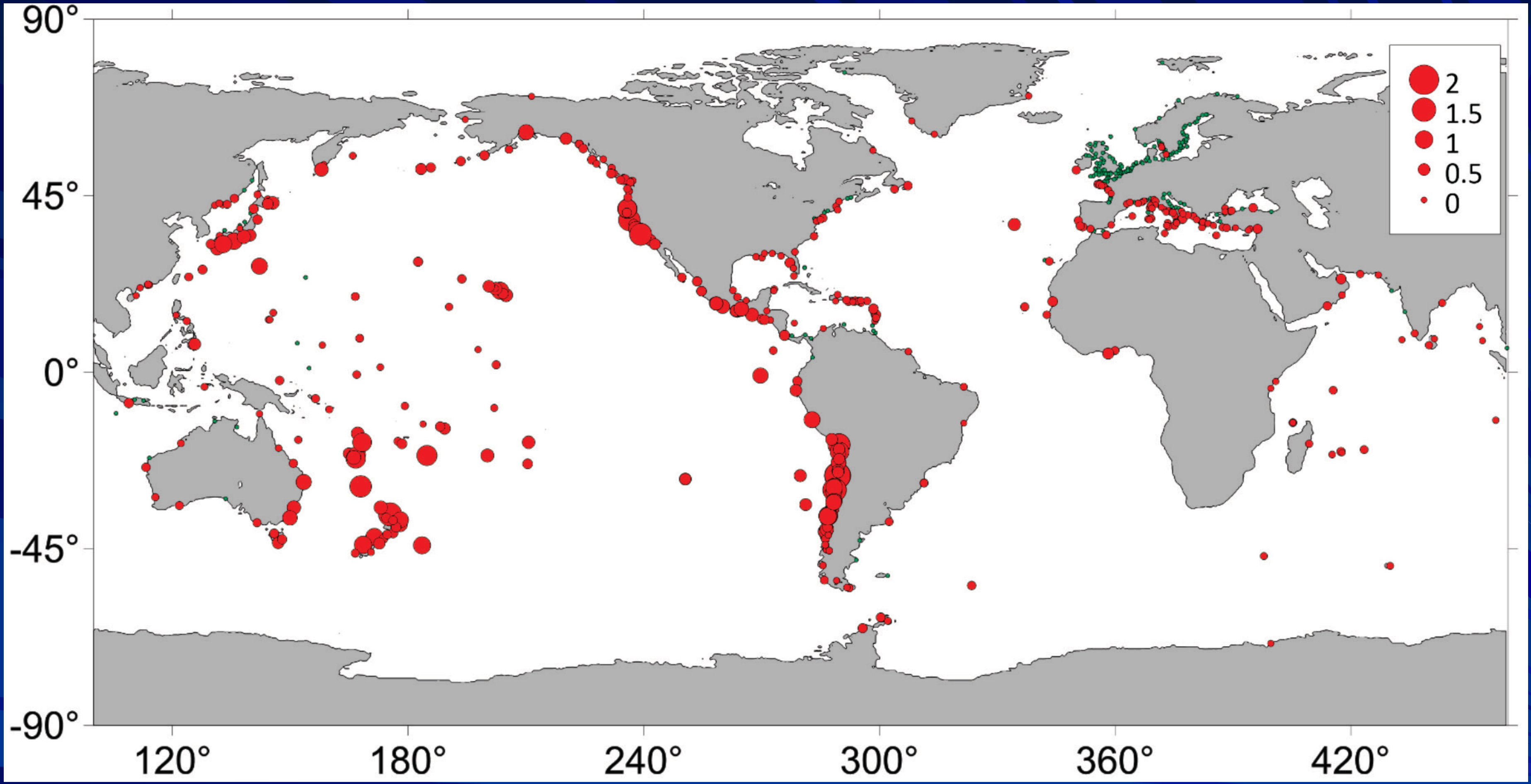
$S_s(w)$ = Open-ocean tsunami spectrum

$$R(w) = S_{obs}(w) / S_{bg}(w)$$



(from Zaytsev et al., 2023)

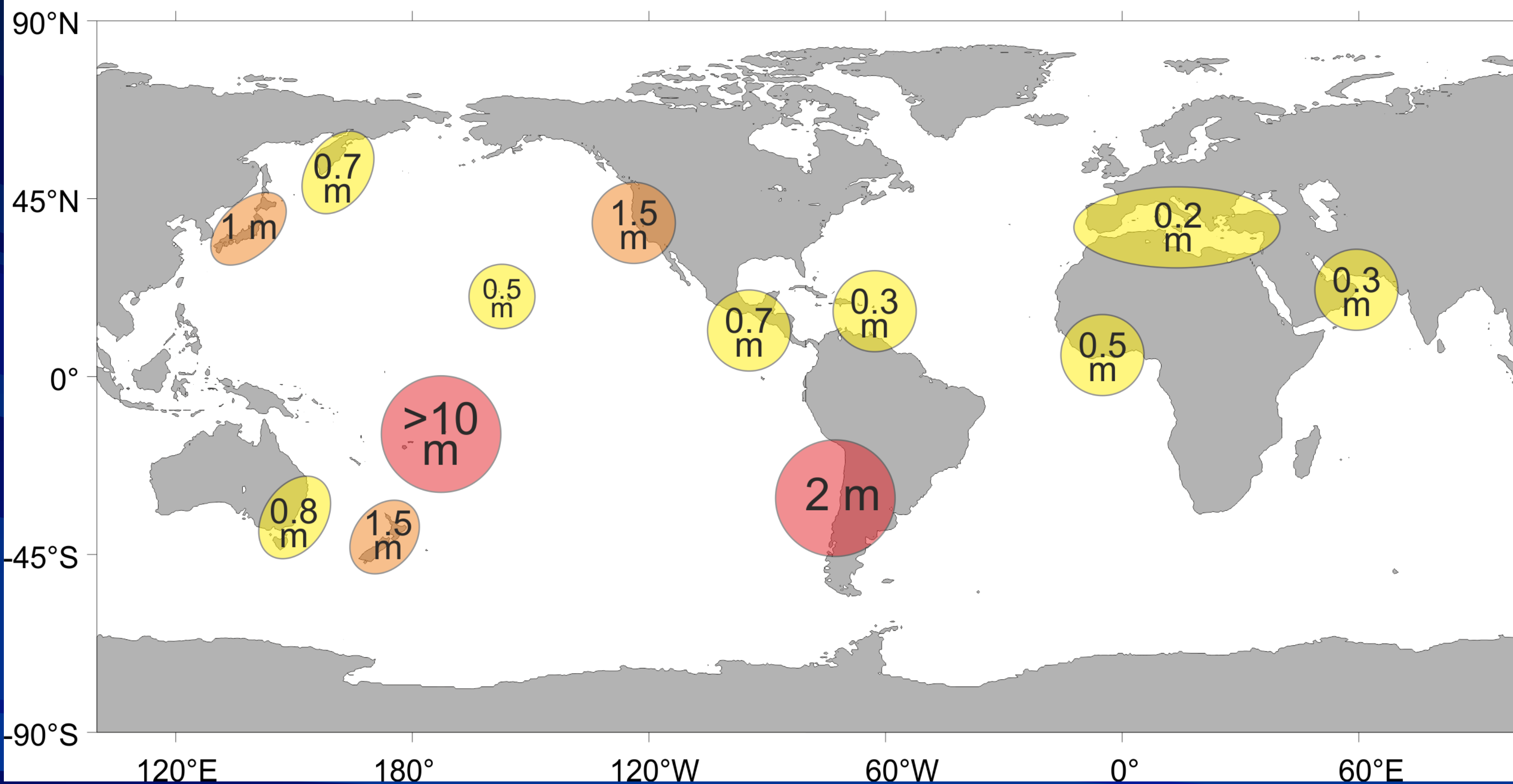
Maximum recorded 2022 Tonga tsunami amplitudes



Constructed by Igor Medvedev

From *Joint team* [2022] (Isaac Fine, Jadranka Šepić, Igor Medvedev, Richard Thomson and Alexander Rabinovich)

Maximum amplitude of the tsunami (m)



Constructed by Igor Medvedev

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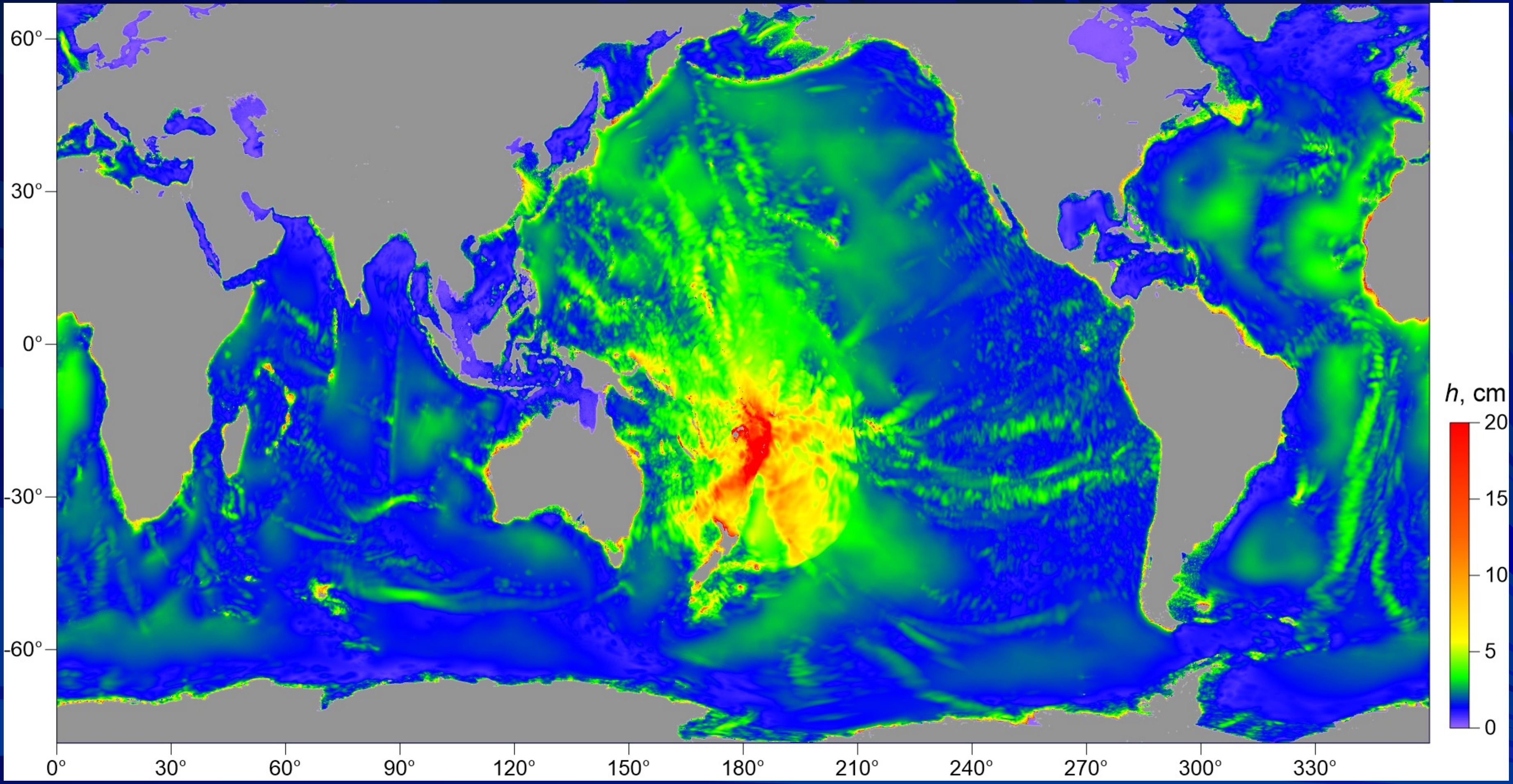
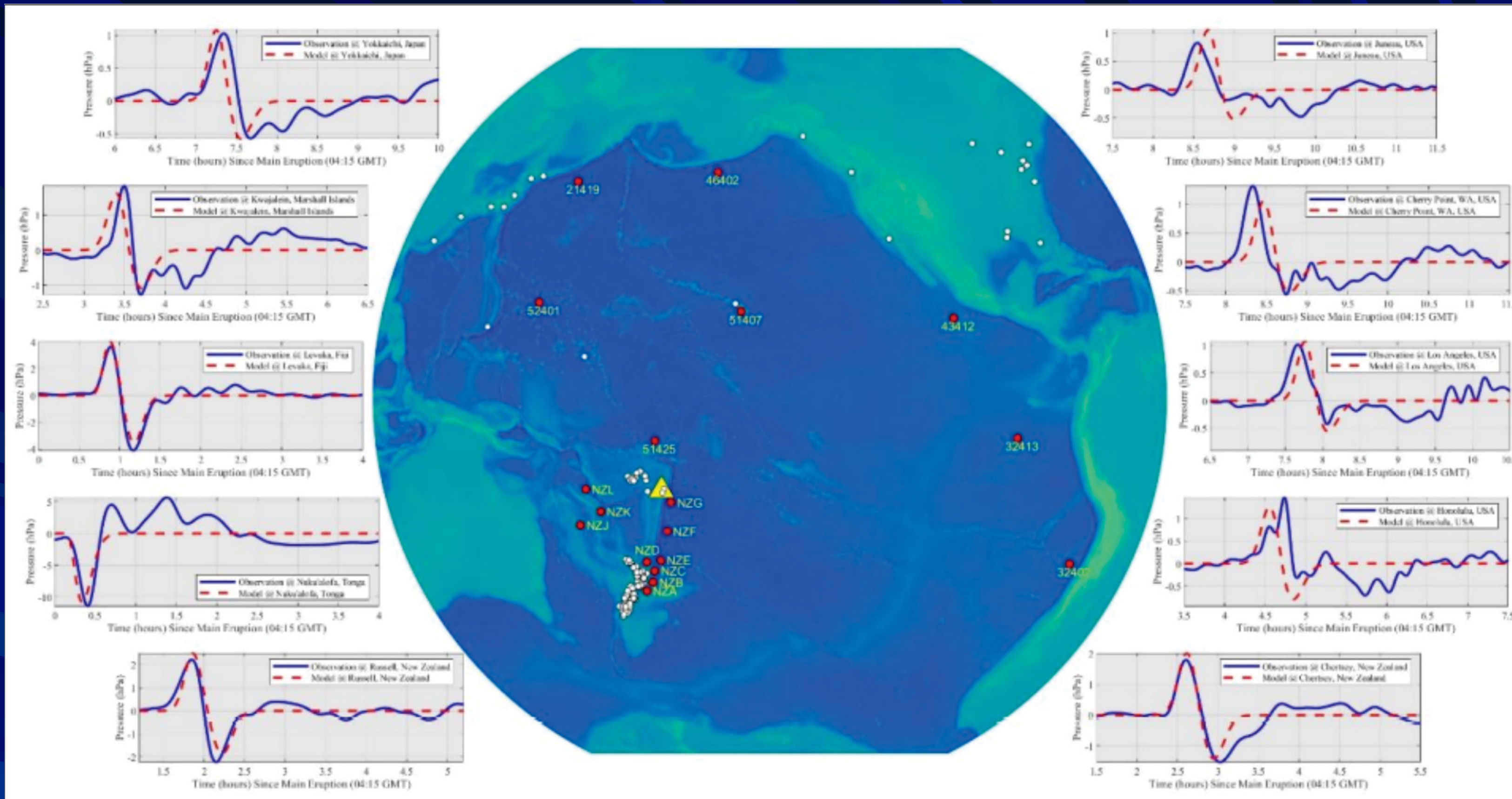
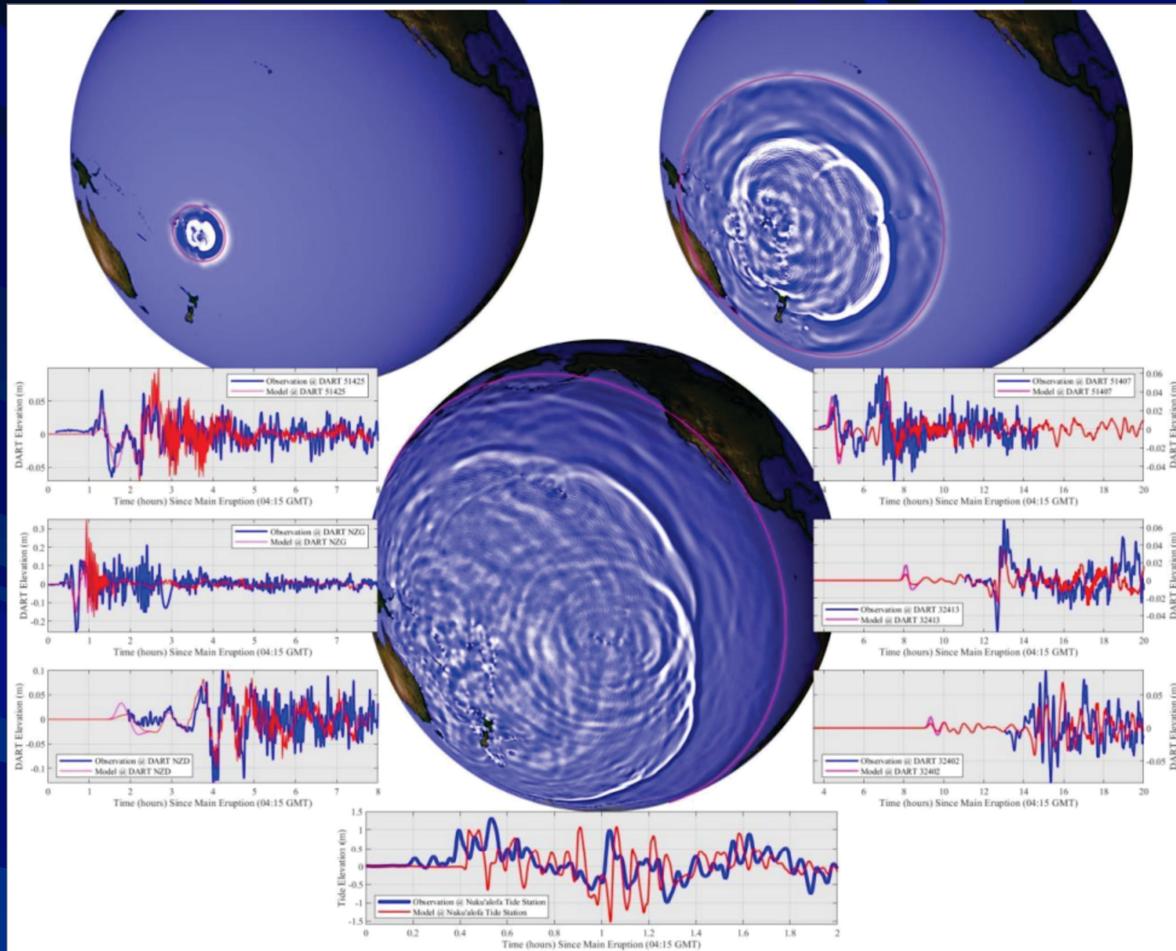
- **Numerical modelling**





Observed pressure signals (in hPa), throughout the Pacific used to calibrate the *N*-wave pressure pulse model, and the corresponding location of the station that recorded the signal. Red lines on each time series plot represent the model result; blue lines represent the measured pressure signal. Shown on this map are the 143 weather stations used to calibrate the pressure pulse model (white dots), the deep-sea DART sensors (red dots, with name labels), and the Hunga Tonga volcano (yellow triangle).

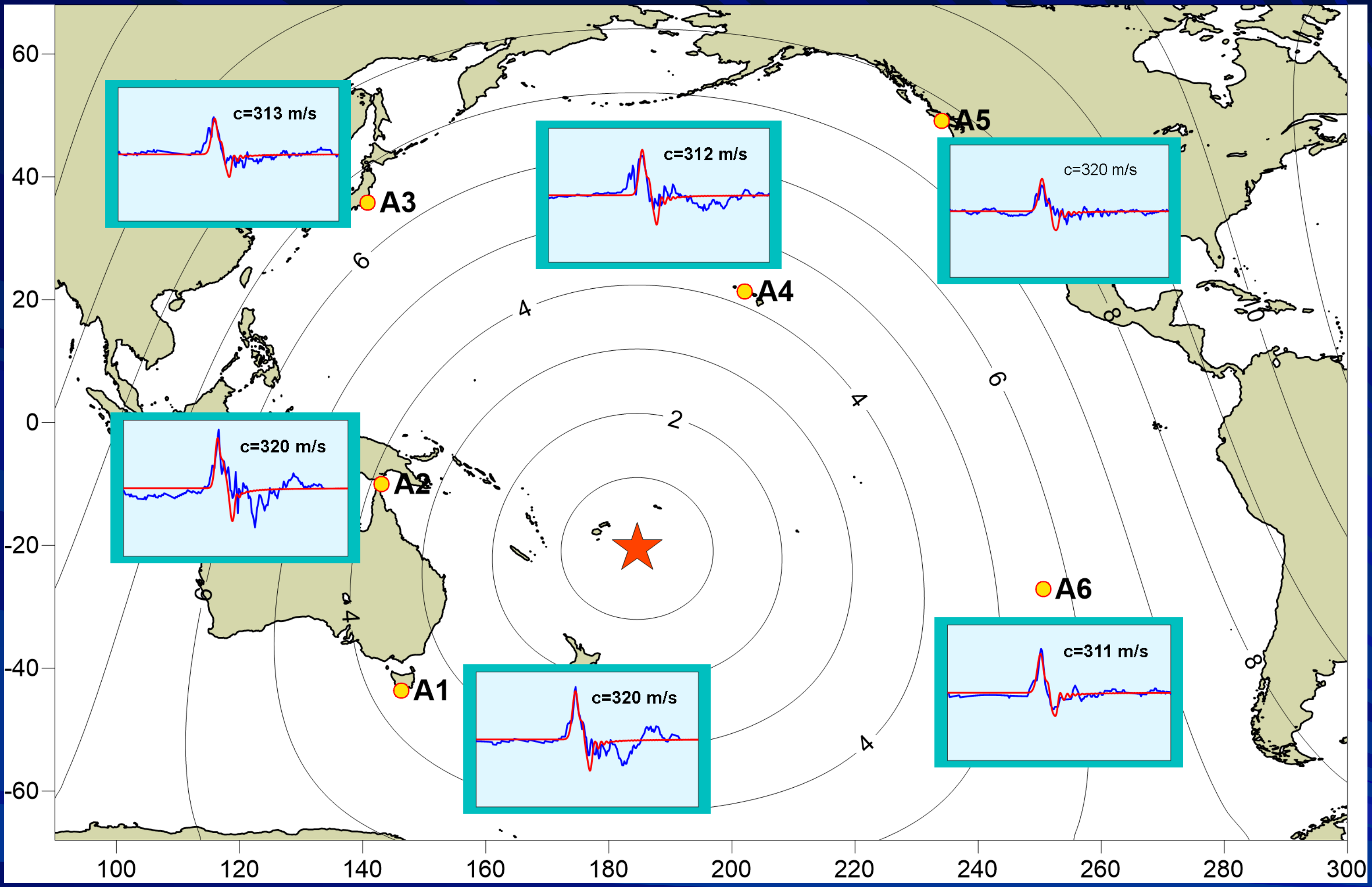
From *Lynett et al.* [2022]



Summary of the simulation results by Lynett et al. [2022] from the highly nonlinear dispersive water wave model recreated for the three tsunamis generated by the 2002 Tonga event. The wave field in the Pacific is shown at 1-hour post-eruption (05:15 UTC) in the upper left, 4 hours post-eruption (08:15 UTC) in the upper right, and 8 hours post-eruption (12:15 UTC) in the lower middle. The crest location of the pressure pulse is given by the magenta line. Model-data comparisons are given in the time series plots at the Nuku’alofa tide station (lower plot) and various DART stations. In the DART comparisons, the red line shows the modeled ocean surface elevation, while the magenta line provides the modeled ocean surface plus the pressure head from the pressure pulse.

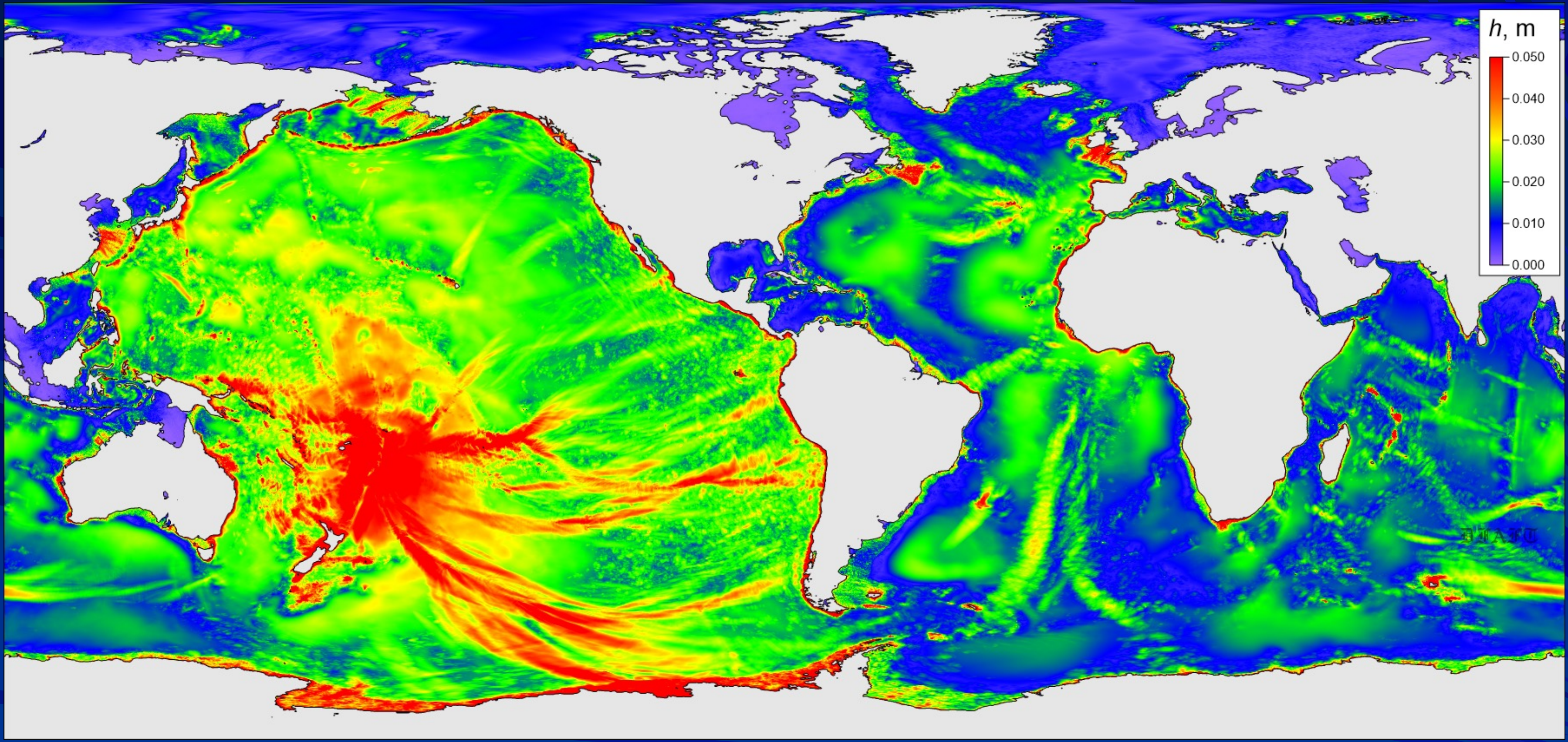
From *Lynett et al.* [2022]

Numerical model of the 2022 Tonga tsunami by Isaac Fine



From *Joint team* [2022] (Isaac Fine, Jadranka Šepić, Igor Medvedev, Richard Thomson and Alexander Rabinovich)

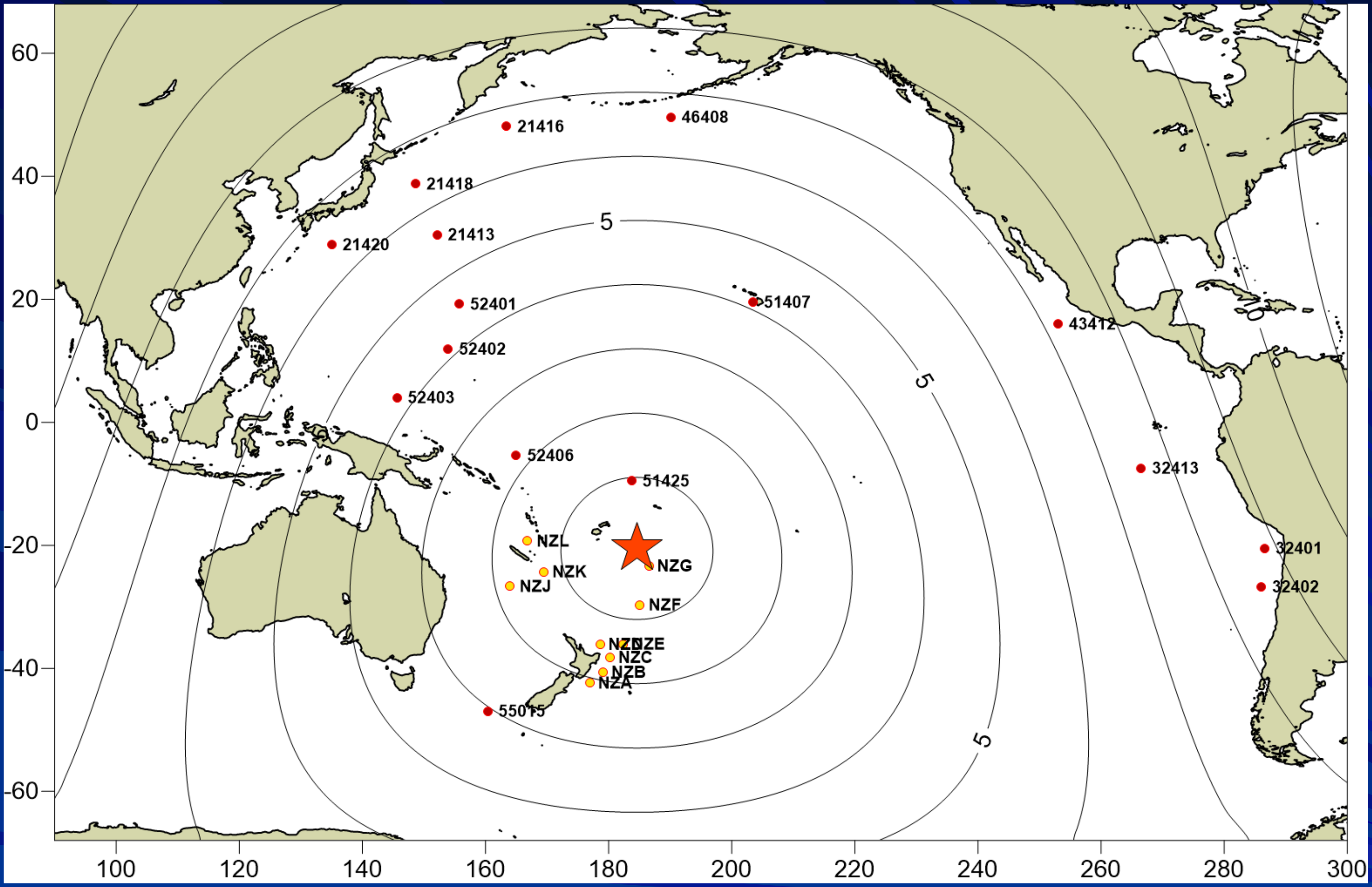
Global numerical modelling of the 2022 Tonga tsunami



Constructed by Isaac Fine

From *Joint team* [2022] (Isaac Fine, Jadranka Šepić, Igor Medvedev, Richard Thomson and Alexander Rabinovich)

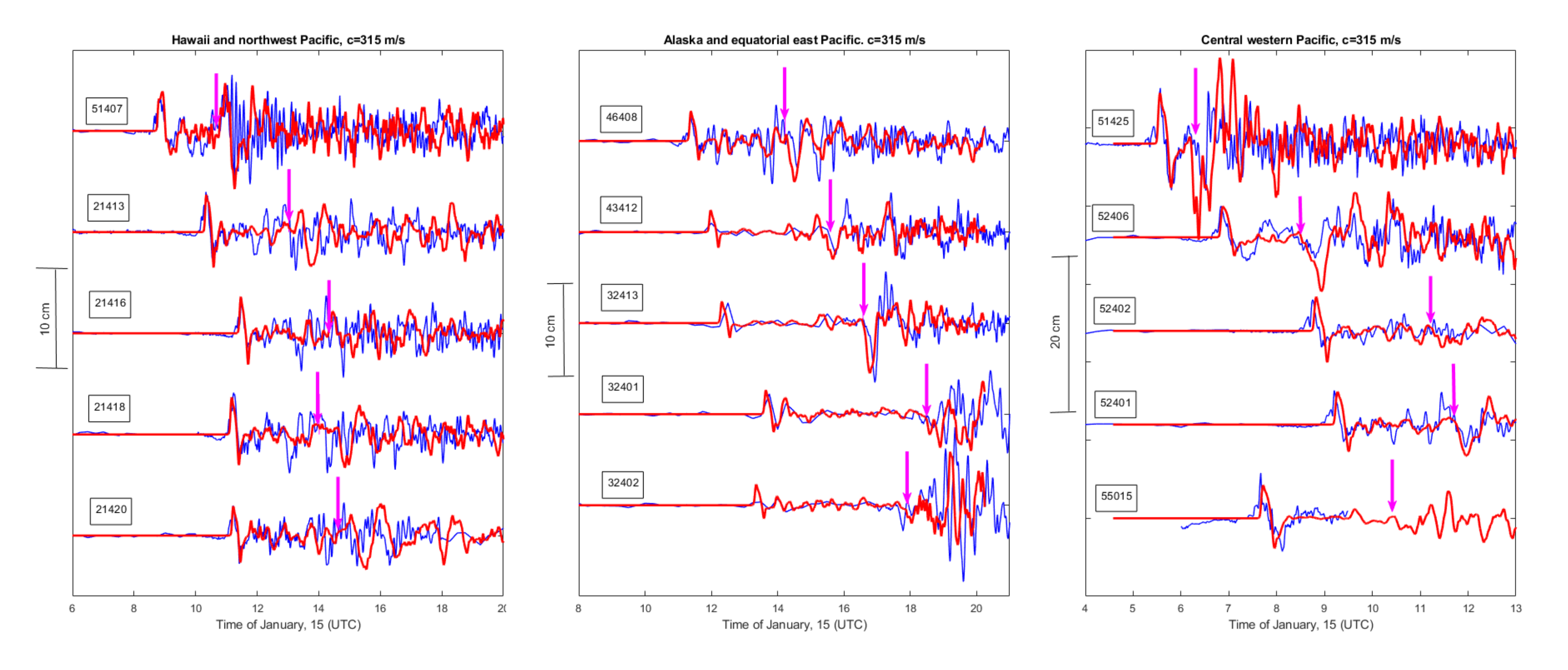
DART stations used to verify the model



Constructed by Isaac Fine

From *Joint team* [2022] (Isaac Fine, Jadranka Šepić, Igor Medvedev, Richard Thomson and Alexander Rabinovich)

Numerically simulated and observed DART records of the 2022 Tonga tsunami



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OF RUSSIAN ACADEMY OF SCIENCES


Thank you! Any questions?