NAMI DANCE Model Applications to Recent Events

Presenters
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University of Bath / 20 November 2023

30 October 2020 Aegean Sea Tsunami Field Observations Along Turkish Coast & Hydrodynamic Simulations with NAMI DANCE

The 30 October 2020 Aegean Sea Tsunami: Post-Event Field Survey Along Turkish Coast

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Introduction

- More than 110-km-long affected coastline, one casualty, several injured people
- Reminder of the tsunami threat after 2017 Bodrum-Kos Tsunami
- The tide gauges located outside the major affected area could not record the observed sizable waves
- Two different field surveys on
- October 31st – November 01st, 2020 and November 04th to November 6th, 2020

Why Post-tsunami Surveys?

- Understand the event and regional effects for developing/improving mitigation tools
- Document the tsunami parameters (water levels, arrival time, inundation extent..)
- Describe the impacts and reducing or increasing factors
- Describe the human behavior and awareness level

Coastal damage observed in 2011 Tohoku tsunami

Damage observed in İzmir coast after 30 October Aegean Sea tsunami

Study Area

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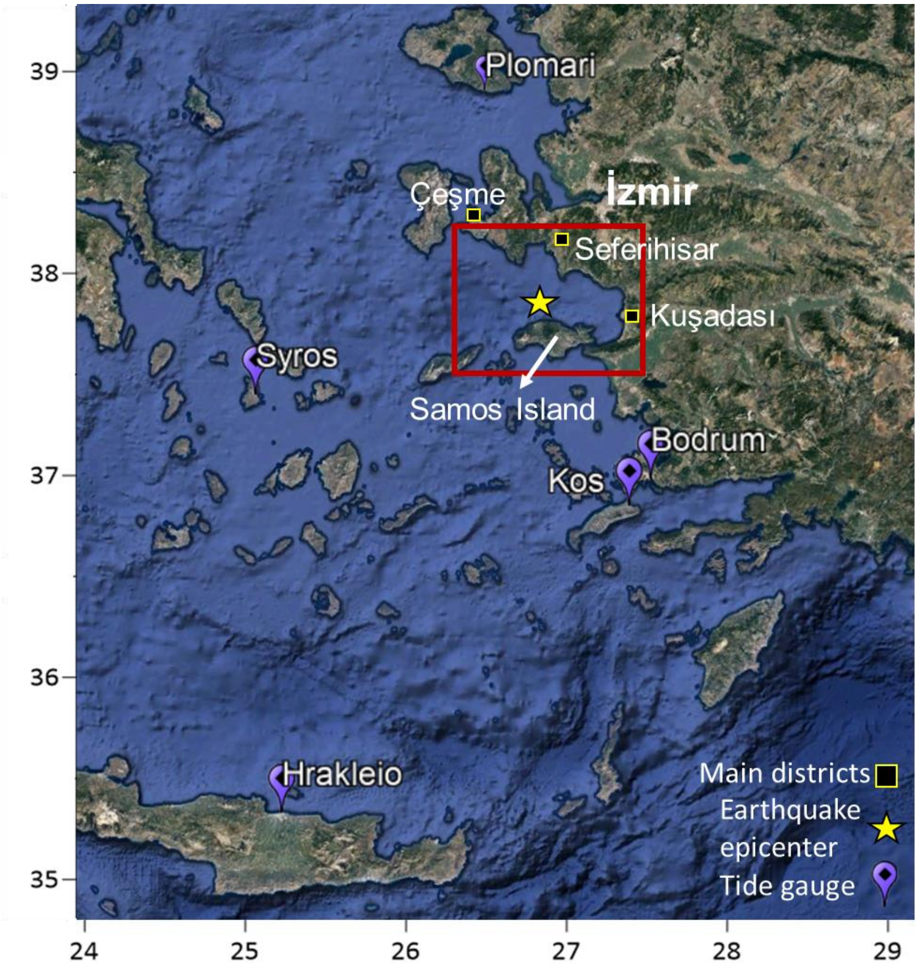
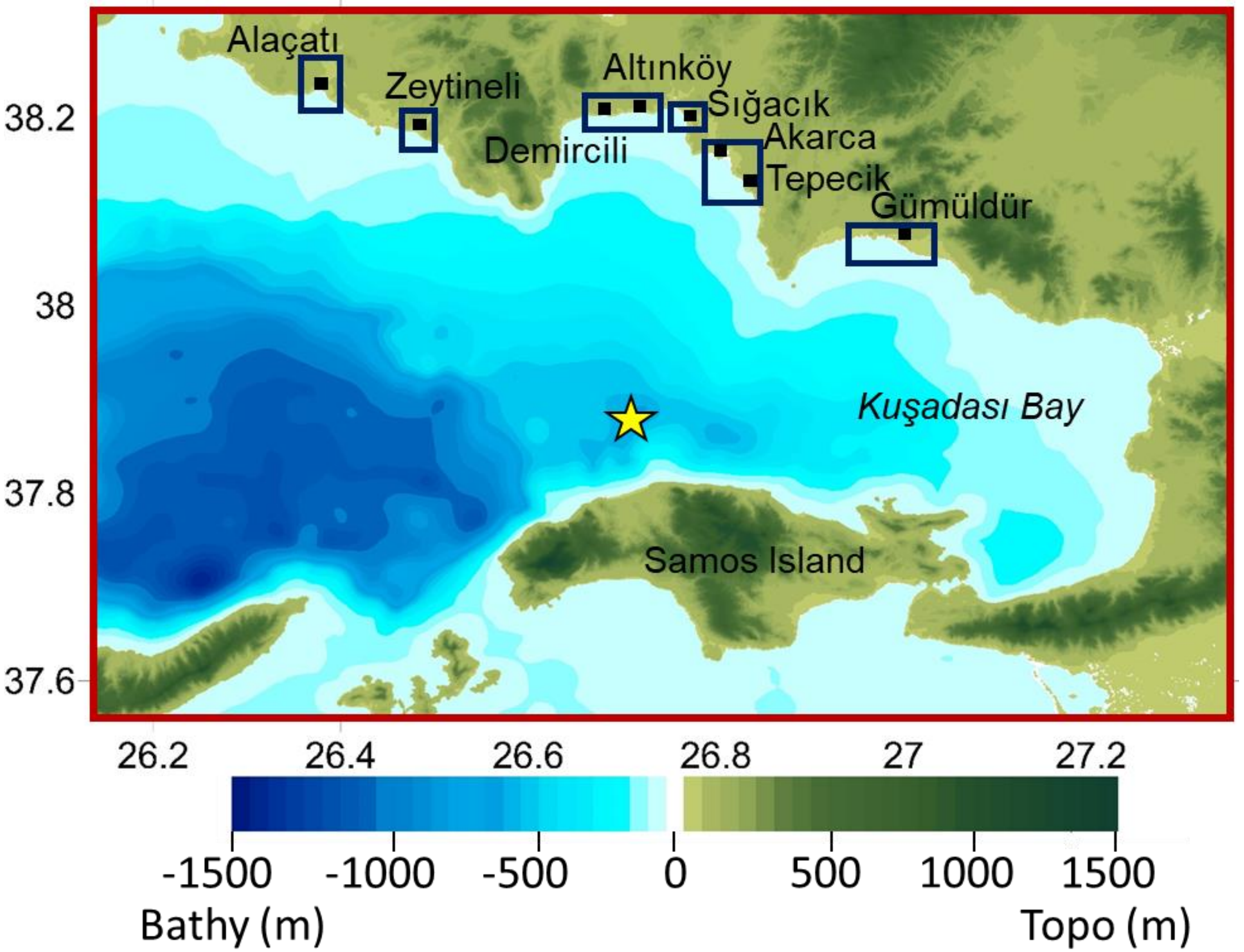
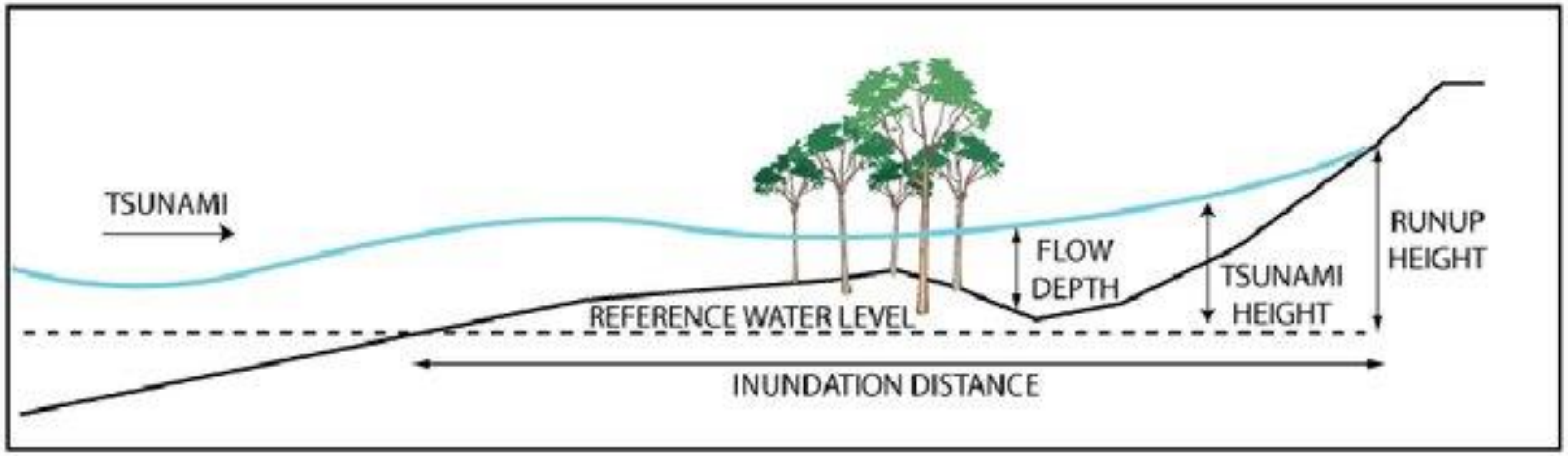




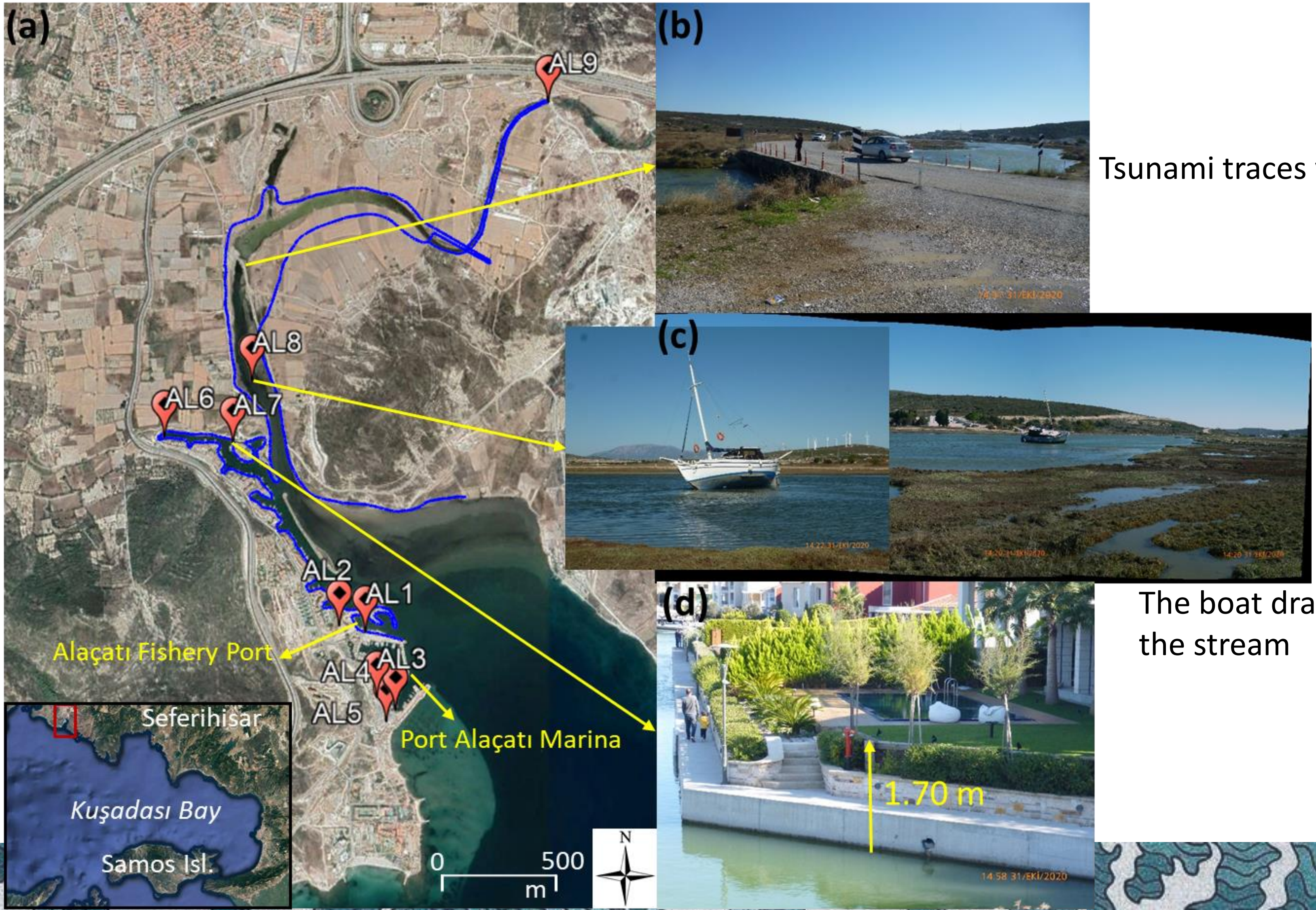
Method



UNESCO-IOC ITST Post -Tsunami Survey Field Guide 2nd Edition (2014)

ALAÇATI

Map showing the surveyed locations in Alaçatı Locality



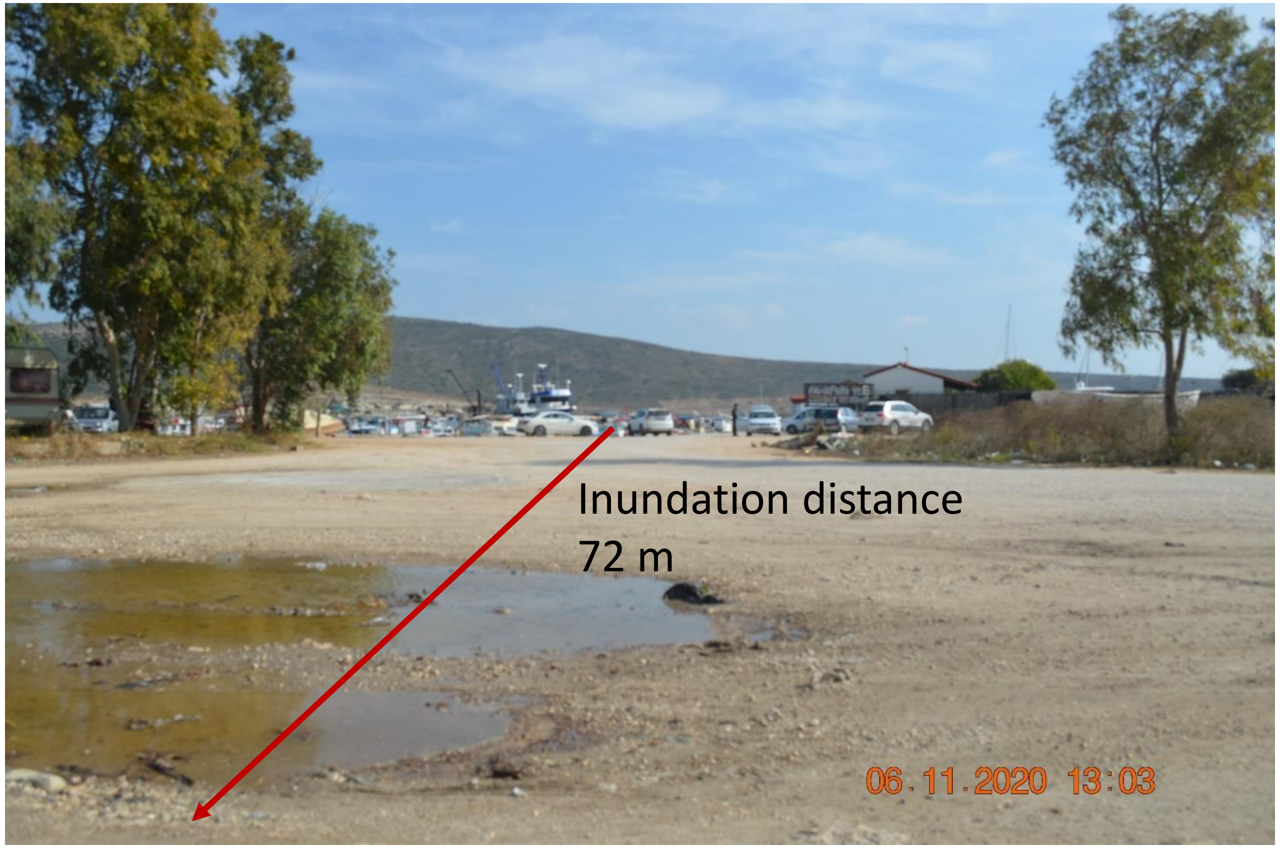
Tsunami traces visible on Alaçatı Azmak bridge

The boat dragged ~1160 m by the tsunami along the stream

*FIELD OBSERVATIONS ALONG TURKISH COAST - **ALAÇATI***

ALAÇATI FISHERY PORT

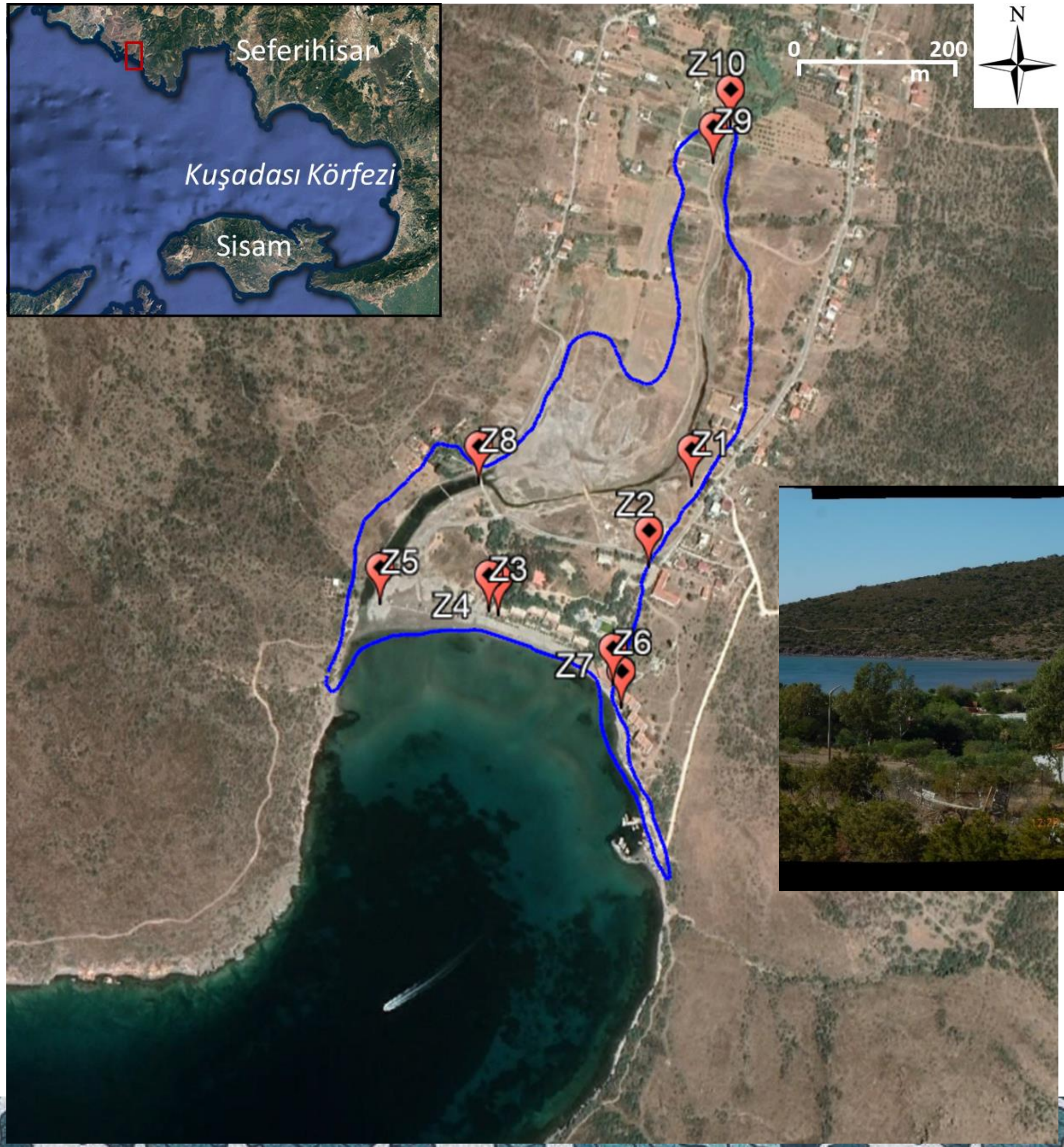
PORT ALAÇATI



Runup: 1.0 m

Flow depth: 0.9 m

FIELD OBSERVATIONS ALONG TURKISH COAST - ***ZEYTİNELİ***



- **1.9 m flow depth on the palm trees, at 50 m from coastline**
- **Maximum tsunami height 2.43 m**
- **Maximum inundation ~760 m**

- Panoramic view of Zeytineli tsunami inundation zone

- Zeytineli survey points and inundation zone (blue line)

FIELD OBSERVATIONS ALONG TURKISH COAST - ***ZEYTİNELİ***

Boat Damage in Zeytineli Fishery Shelter

Abandoned summer houses

FIELD OBSERVATIONS ALONG TURKISH COAST - ***SIĞACIK***

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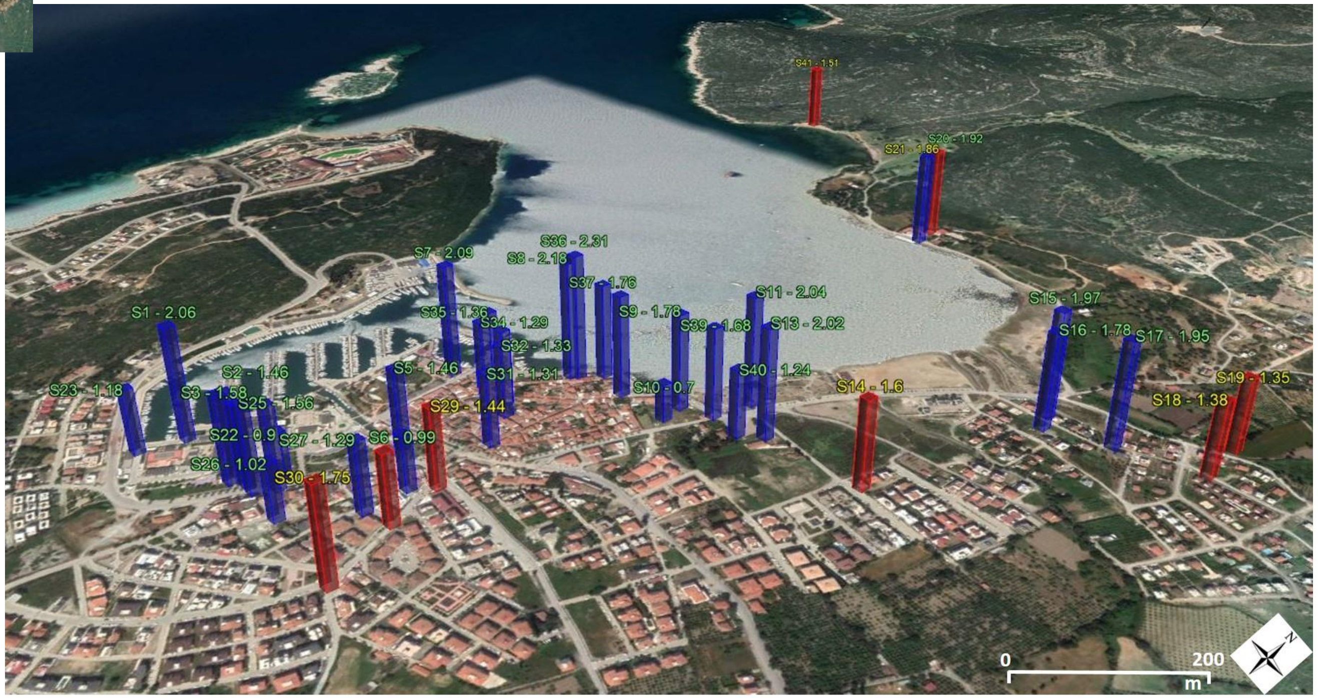
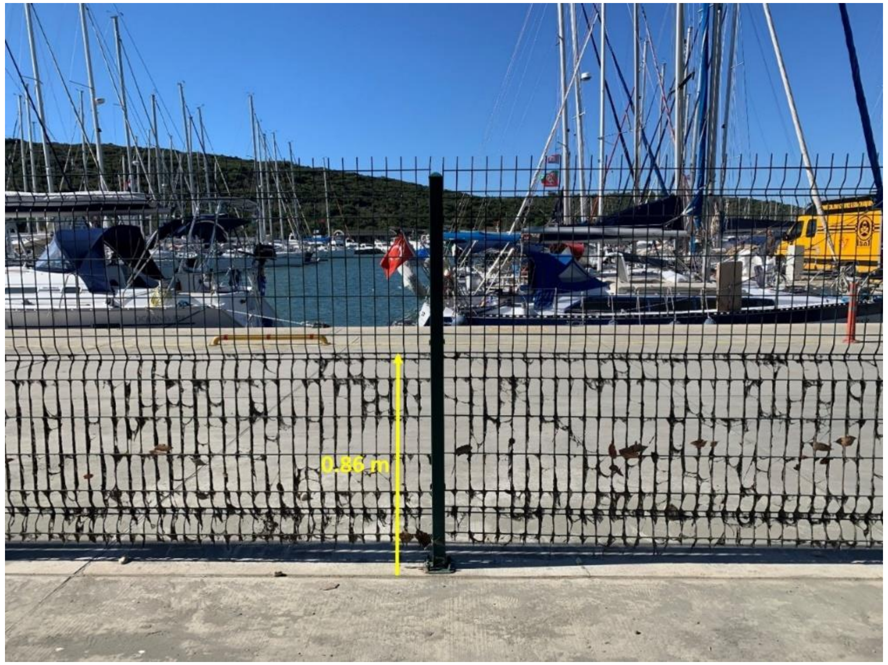
- **Highest impact with one casualty, injured people**
- **Significant damage and extensive property loss in Teos Marina and Kaleiçi region**
- **Maximum tsunami height 2.31 m**
- **Maximum inundation 415 m**



Distribution of the measured tsunami heights (blue) and runup heights (red)in Sığacık

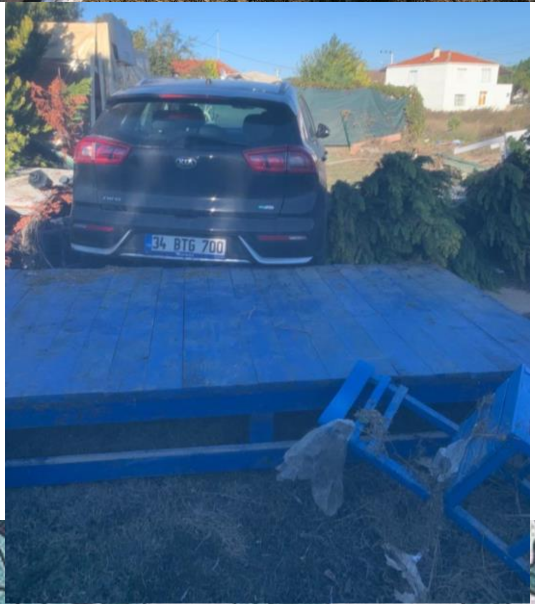
*FIELD OBSERVATIONS ALONG TURKISH COAST - **SIĞACIK***

TEOS MARINA



Tsunami traces on the garden fence of Teos Marina, flow depth of 0.86 m

Heavily damaged cafes and shops in Kaleiçi region



FIELD OBSERVATIONS ALONG TURKISH COAST - *SUMMARY*

Region/ Maximum tsunami parameter	Zeytineli	Sığacık	Akarca
Tsunami height/runup (m)	2.43	2.31	3.82
Inundation(m)	760	415	285

- Most impacted areas were Zeytineli, Sığacık, and Akarca
- Significant amplification in small bays with narrow entrances, highly localized tsunami effects
- Further tsunami inundation and impact at low-lying areas around local streams, «Azmak»
- Tsunami penetration along Alaçatı Azmak ~2.5 km
- Almost no significant inundation or other indications of tsunami impact beyond Gümüldür
- Most of the damage in poorly-engineered coastal structures, i.e., fishery shelters.
- Remarkable increase of tsunami awareness among the population

NAMI DANCE Overview

- **NAMI DANCE Overview**
  - Solves the nonlinear form of shallow water equations.
  - Uses water surface disturbances as inputs.
  - Simulates propagation and coastal amplification of long waves.

- **Computational Methods**
  - Nonlinear forms of long-wave equations are solved.
  - Operates in nested domains with a rectangular structured mesh.

- **Development and Upgrades**
  - Developed from TUNAMI N2 for solving tsunamis.
  - Later upgraded to NAMI DANCE, incorporating GPU for high-speed processing.
  - Upgraded version known as NAMI DANCE SUITE for tsunamis and tropical cyclones.

- **Visualization**
  - Provides a 3D view of wave propagation during simulations.

- **Applications**
  - Applied to specific long wave benchmark problems.
  - Successfully reproduced several tsunami events.

- **References:**

  - Original development and upgrades (Yalciner et al. 2002; 2004; Zahibo et al. 2003; Zaitsev et al. 2008; Yalciner et al. 2014; Aytore et al. 2016; Cankaya et al. 2016; Kian et al. 2016; Velioglu et al. 2016, Zaytsev et al. 2016, Zaytsev et al. 2019, 2020).
  - GPU integration and high-speed processing (Yalciner B. and Zaytsev A. 2017).
  - Application to benchmark problems and tsunami events (Yalciner et al. 2008; Lynett et al. 2017, Sogut, 2018; Sogut and Yalciner, 2019; Tufekci et al. 2018; Bilgin 2019).

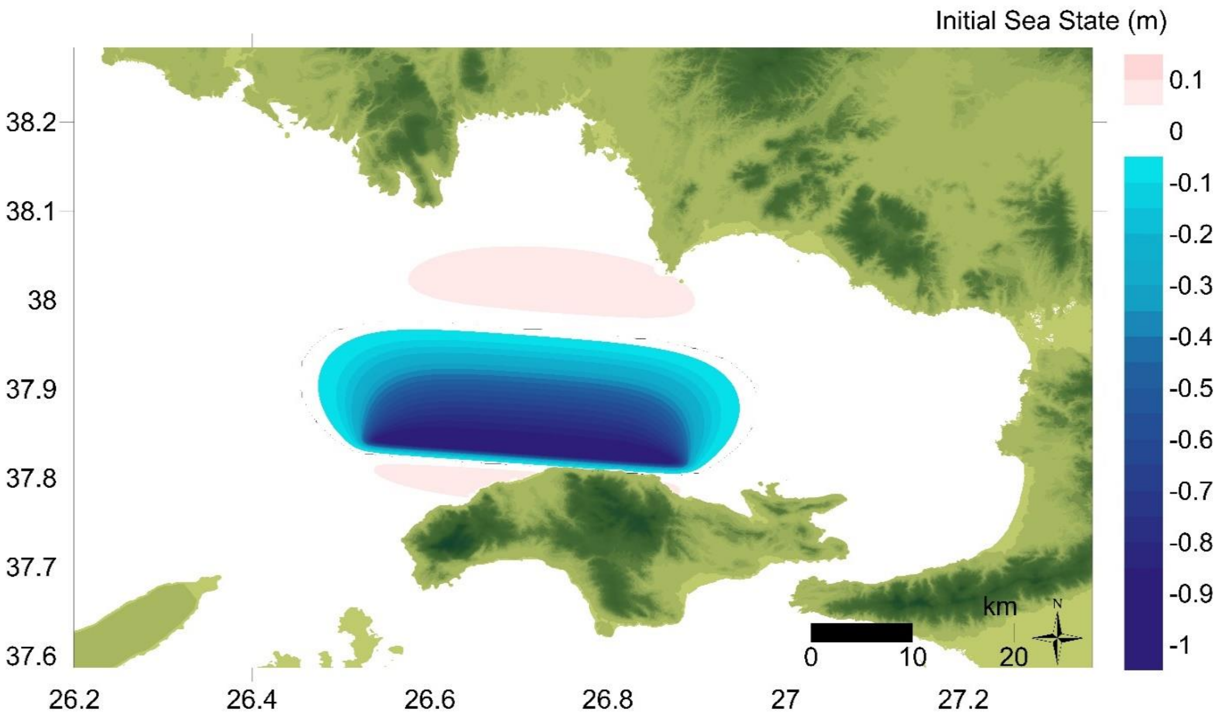
$$\frac{\partial M}{\partial t}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\lambda}\left(\frac{M^2}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}\left(\frac{MN\cos\theta}{D}\right)+ +\frac{gD}{R\cos\theta}\frac{\partial\eta}{\partial\lambda}+\frac{gn^2}{D^{7/3}}M\sqrt{M^2+N^2}=fN, \quad (1)$$

$$\frac{\partial N}{\partial t}+\frac{1}{R\cos\theta}\frac{\partial}{\partial\lambda}\left(\frac{MN}{D}\right)+\frac{1}{R\cos\theta}\frac{\partial}{\partial\theta}\left(\frac{N^2\cos\theta}{D}\right)+ +\frac{gD}{R}\frac{\partial\eta}{\partial\theta}+\frac{gn^2}{D^{7/3}}N\sqrt{M^2+N^2}=-fM, \quad (2)$$

$$\frac{\partial\eta}{\partial t}+\frac{1}{R\cos\theta}\left[\frac{\partial M}{\partial\lambda}+\frac{\partial}{\partial\theta}\left(N\cos\theta\right)\right]=0, \quad (3)$$

Hydrodynamic Simulations with NAMI DANCE

Initial Water Level



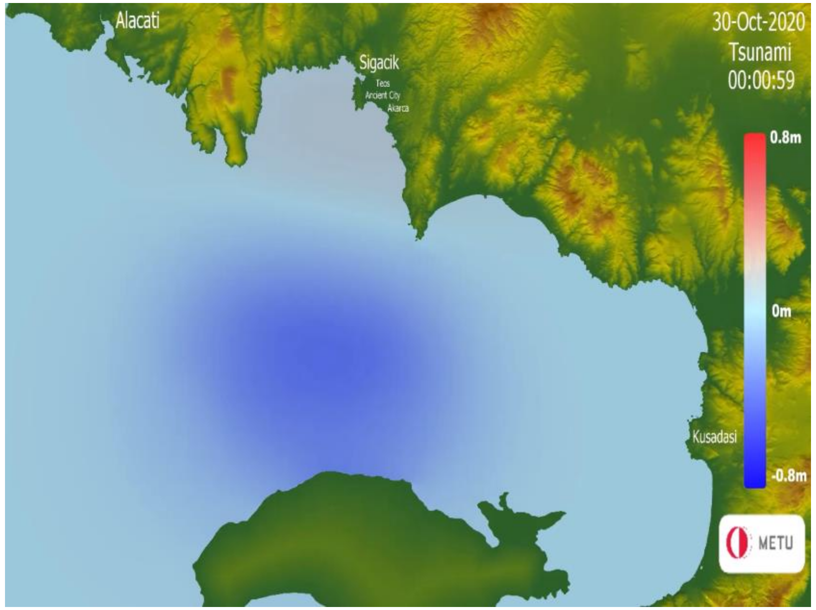
The fault parameters used to create the source (initial water level) of the tsunami are as follows:

Lon/Lat	Length (km)	Width (km)	Depth (km)	Dip (°)	Strike (°)	Rake (°)	Slip (m)
26.725/37.890	36	18	11.5	37	276	-88	1.80

(Ganas et al. 2020

30 October 2020 Aegean Sea Tsunami

Hydrodynamic Simulations with NAMI DANCE



Source model for tsunami generation is obtained from Ganas et al., 2020.

Numerical modelling studies of the Samos-Seferihisar tsunami

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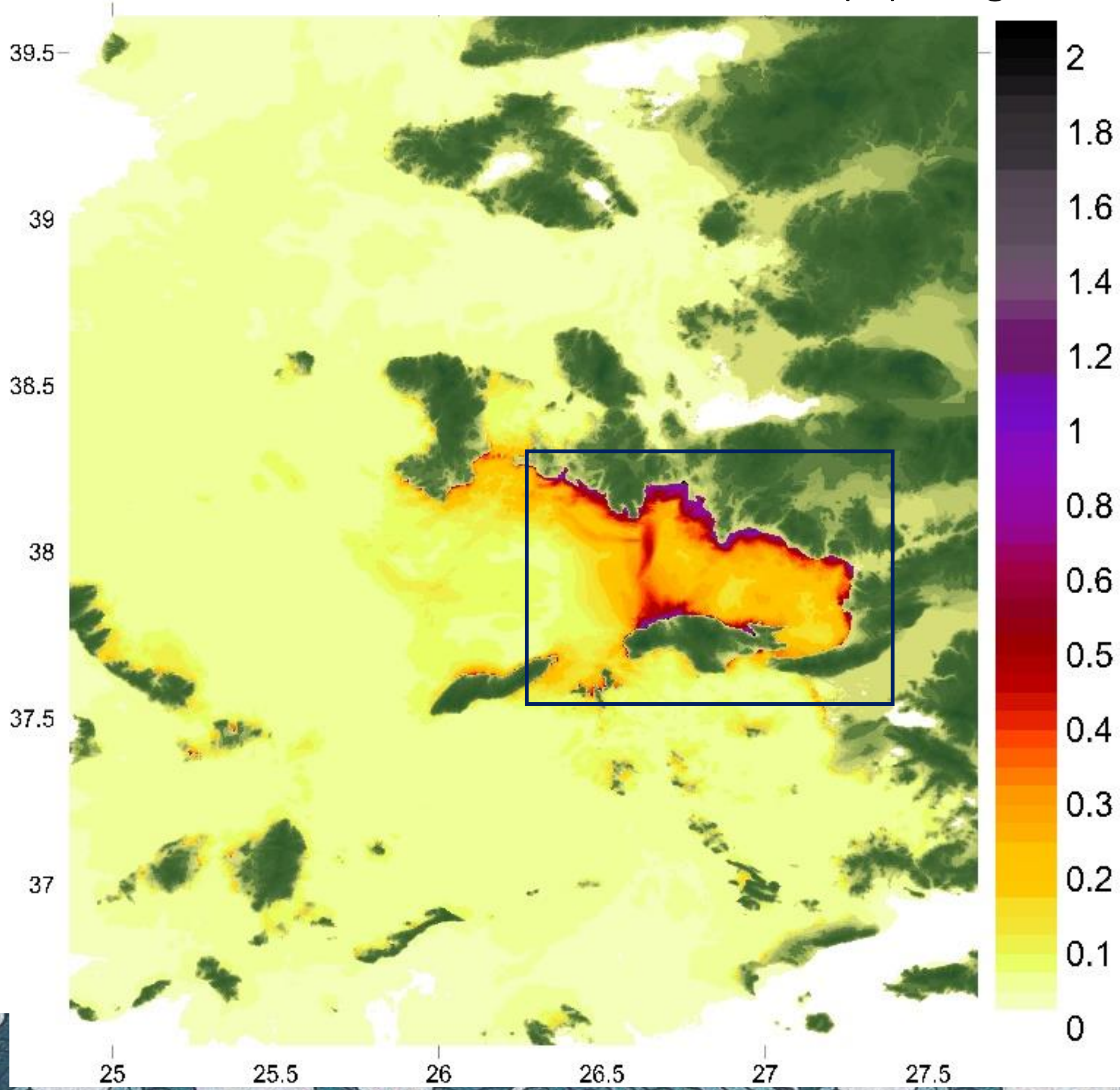
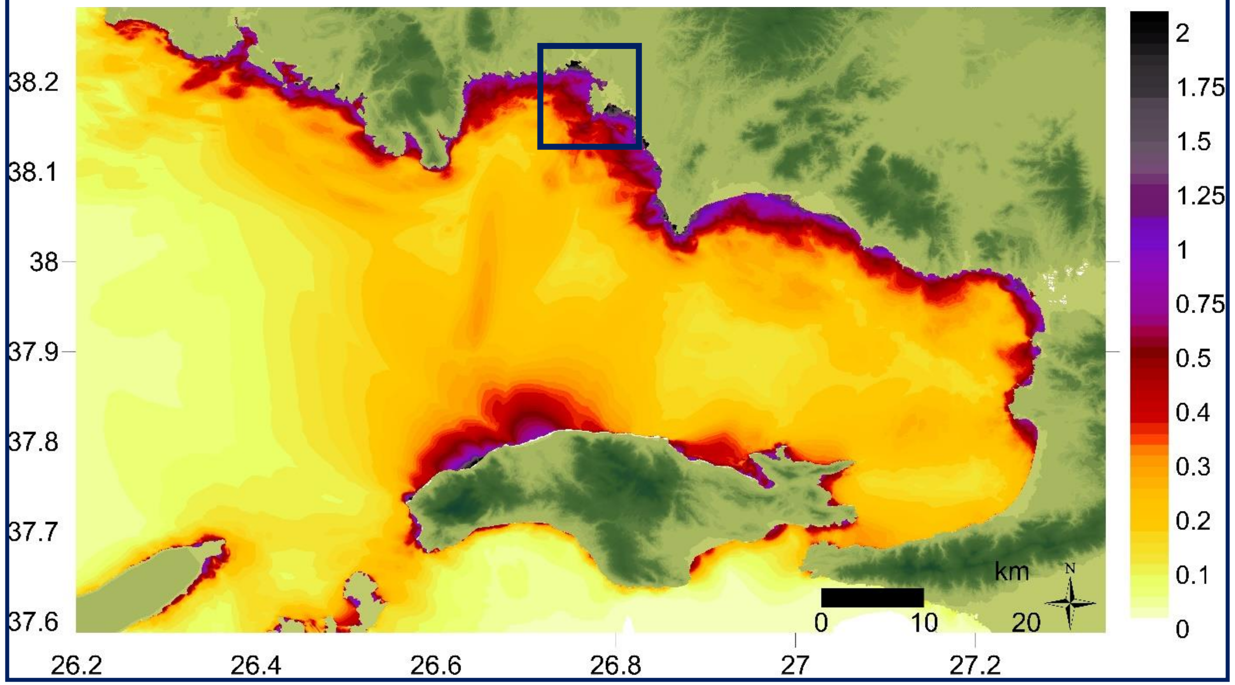
Distribution of Maximum Water Level (m) - Aegean Sea



Distribution of Maximum Water Level (m) – Kuşadası Bay



Numerical modelling studies of the Samos-Seferihisar tsunami

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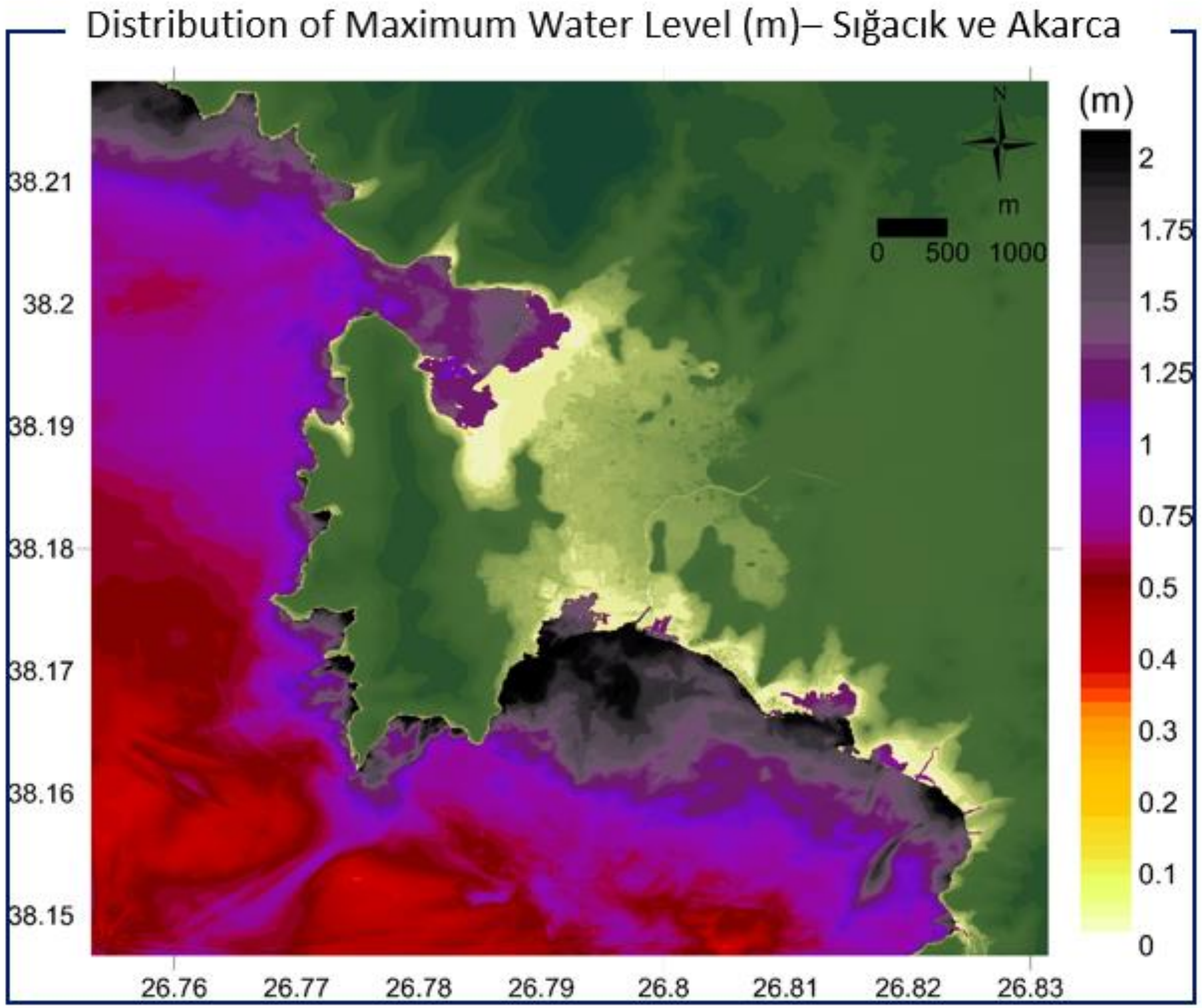
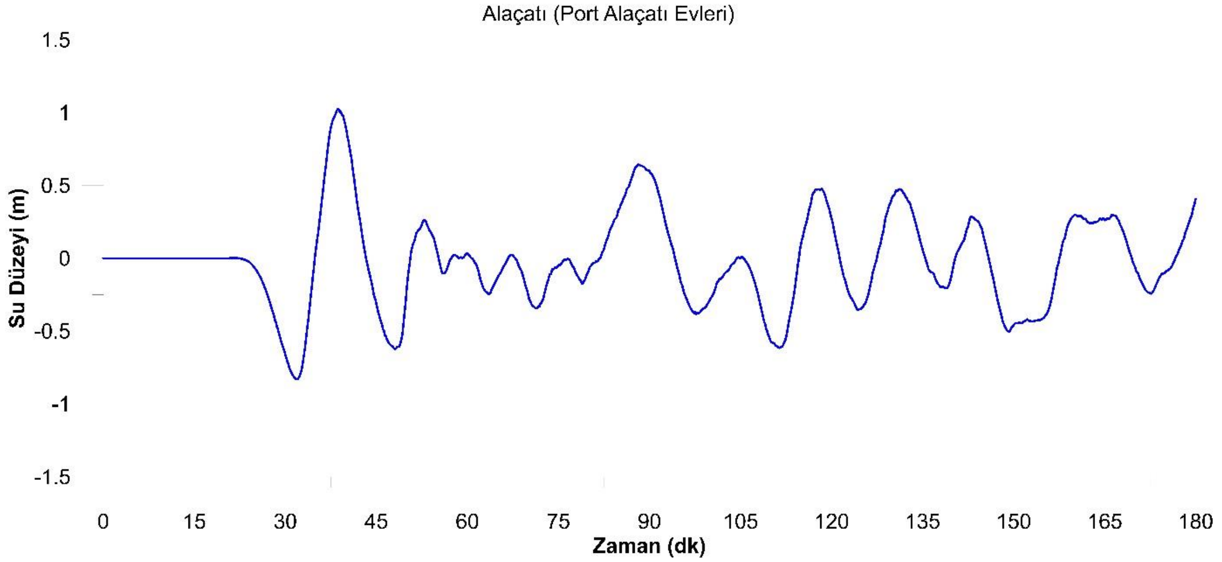
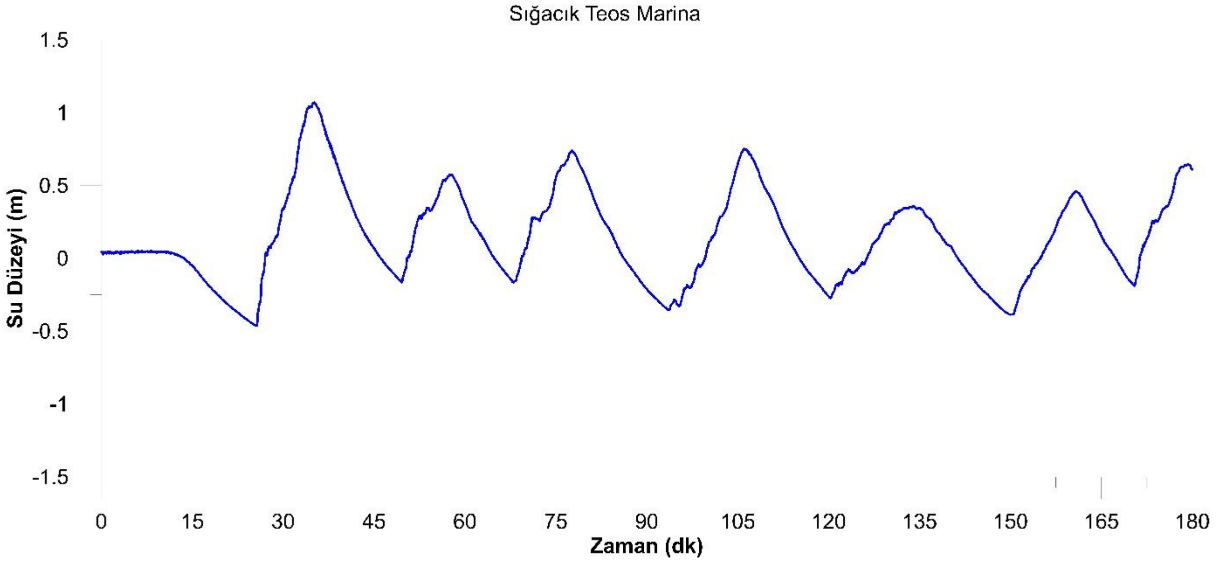
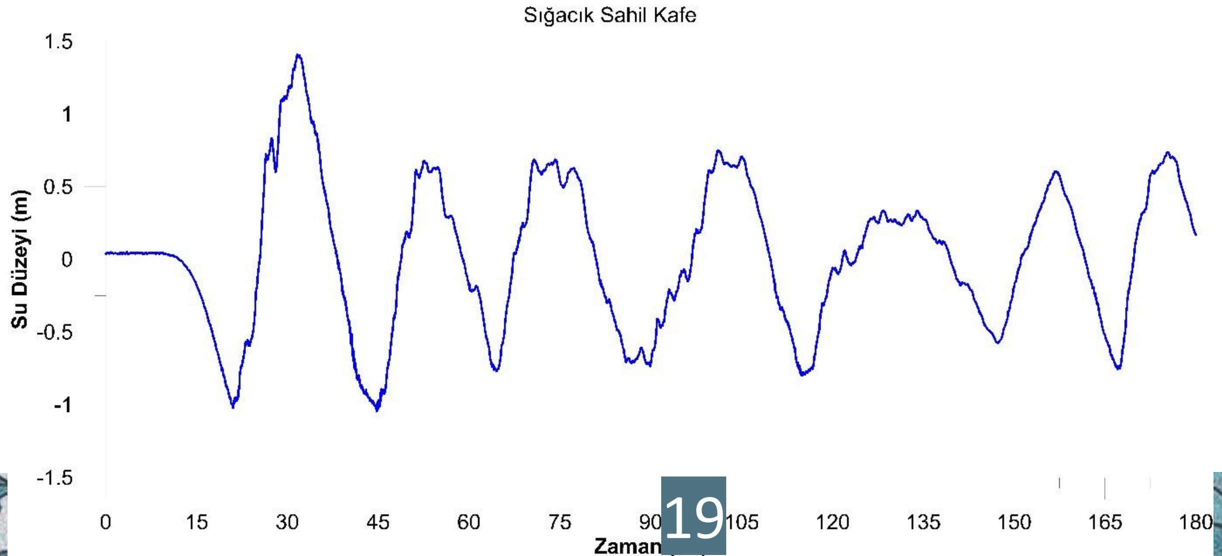


Numerical modelling studies of the Samos-Seferihisar tsunami

Water level changes calculated at observation points as a result of modeling







Numerical modelling studies of the Samos-Seferihisar tsunami

Comparison Table of Wave Arrival Times - Observation vs. Modelling Results

SIĞACIK TEOS MARINA

Video Recording	Event	Modelling Result
14.51	Earthquake	14.51
15.08	Beginning of the decrease in sea level	15.17
15.13	Significant drop in water level	15.20
15.14	Rise in water level up to the dock level	15.23
15.16	Water level is exceeding the dock	15.25
15.17	Cameras are stopping operation due to flooding	-

SIĞACIK BEACH CAFE

Video Recording	Event	Modelling Result
14.51	Earthquake	14.51
15.01	The water level is decreasing by approximately 0.5 m	15.08
15.04	Significant drop in water level	15.13
15.08	Inundation progress is starting	15.21
15.10	Max. water level	15.23

PORT ALAÇATI RESIDENCES

Video Recording	Event	Modelling Result
14.51	Earthquake	14.51
15.13	The water level is decreasing by approximately 0.5 m	15.20
15.19	Min water level	15.23
15.26	Max. water level	15.30

MEASURES THAT CAN BE TAKEN TO MITIGATE TSUNAMI RISK

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- One effective method for tsunami protection, such as **coastal walls** but is not a preferred option due to its hindrance to the community's connection with the sea and coast.

- Increase the **crest height** of breakwaters

- **Rapid Evacuation** in Tsunami-Prone Areas

- **Coastal Afforestation's** Role in Tsunami Mitigation

- Optimal **Evacuation Route Determination** for Each Coastal Region:

THANK YOU!

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha'apai Eruption with NAMI DANCE Suite

Global propagation of air pressure waves and consequent ocean waves due to the January 2022 Hunga Tonga-Hunga Ha'apai eruption

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Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha'apai Eruption

Introduction

- On January 15, 2022, following prior volcanic activity, a violent eruption of the Hunga Tonga-Hunga Ha'apai (HTHH) volcano (20.546◦S, 175.390◦W) occurred at 04:15 UTC (USGS, 2022) and generated a large tsunami that caused serious damage in many of the Tonga Islands.

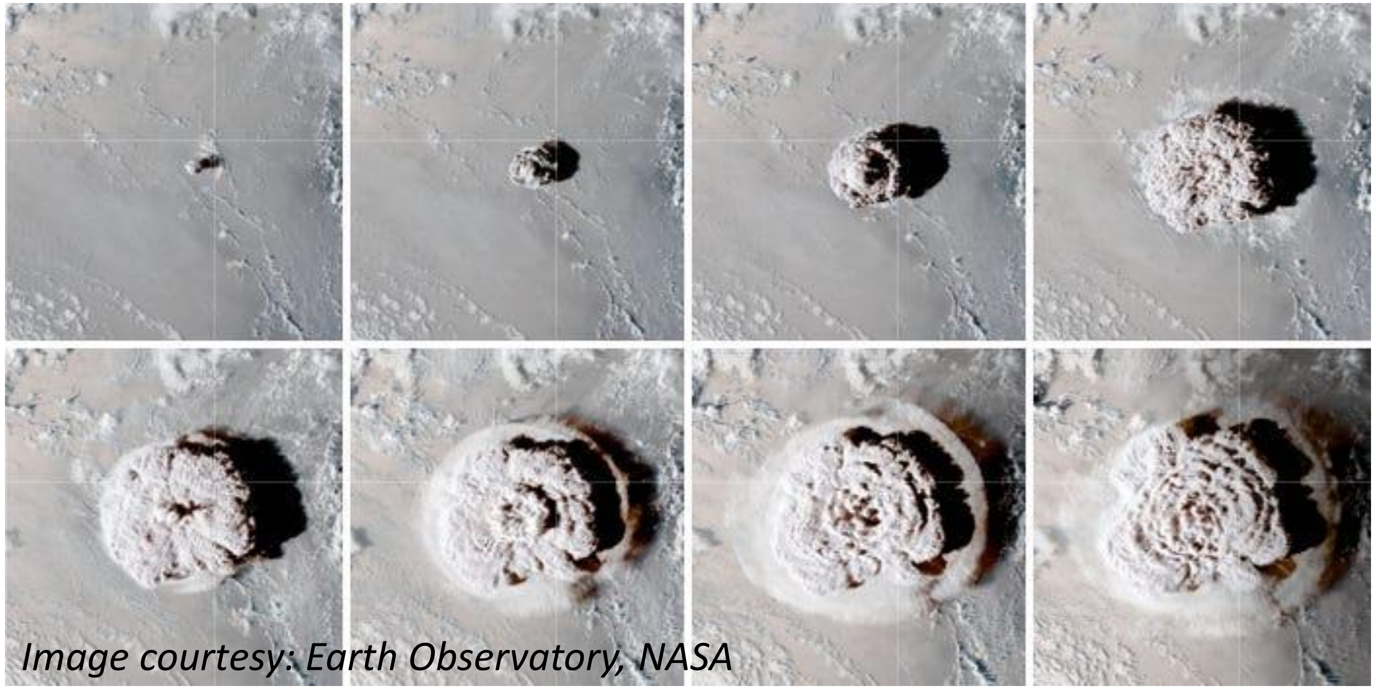

Figure 1. A sequence of still images from the GOES-17 satellite on January 15, 2022

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha'apai Eruption

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Introduction

- Shock waves were emanated from the island following the eruption and radiated outward at close to the speed of sound, reached a stable state after ~5 km (Lynett et al, 2022).
- Those air waves formed in the mid-stratosphere and circled Earth for days as a positive pressure pulse generating particular conditions over the ocean surface that caused an atmospheric pressure induced tsunami (Dogan et al. ,2022).

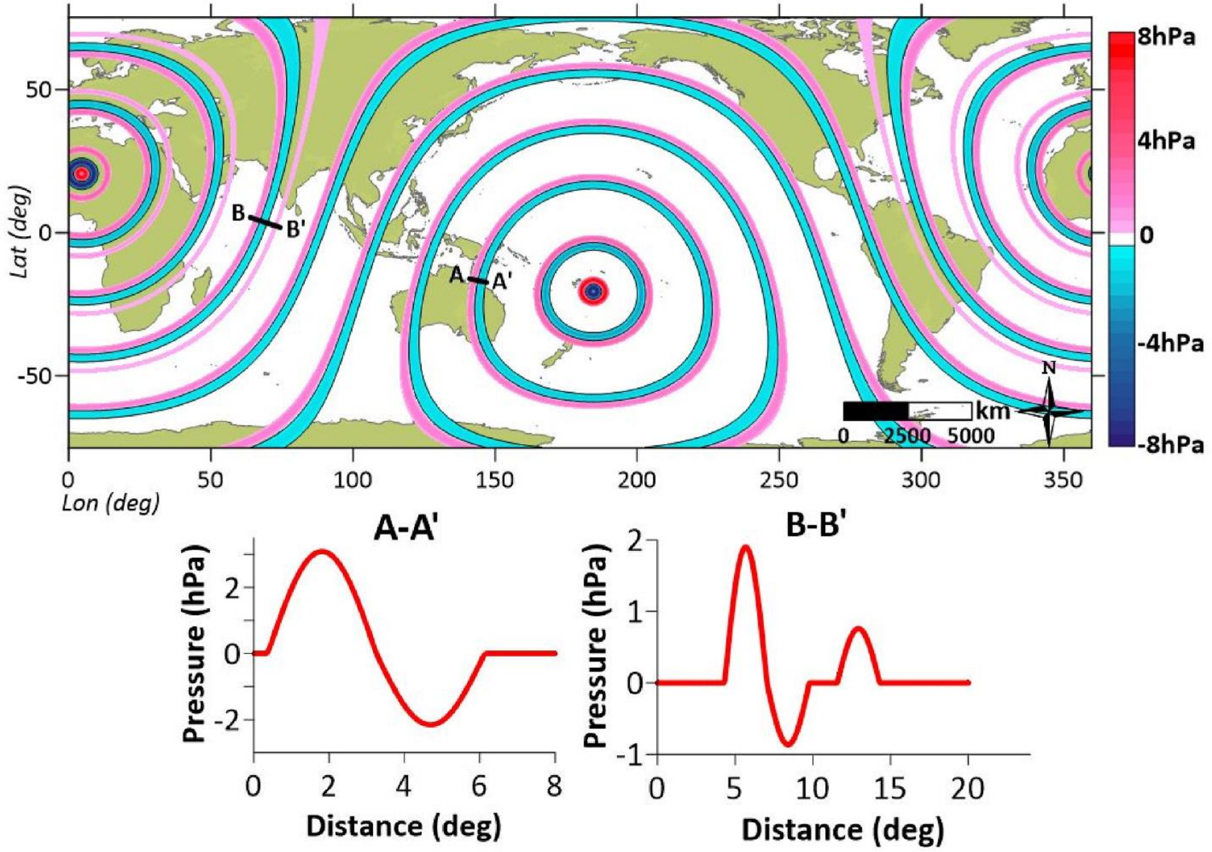

Figure 2. Map of computed pressure fields for every 2h based on synthetic model (Dogan et al., 2022).

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha'apai Eruption

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Objectives of the study

- Investigating the global propagation of the atmospheric pressure oscillations (*first cycle of the pressure waves*) and the consequent ocean waves induced by HTHH Eruption.

- Modelling the air pressure wave and resulting ocean waves with,
  - i) synthetic pressure forcing model based on barometric measurements from different parts of the world
  - ii) a hydrodynamic model based on nonlinear shallow water theory using initial disturbance at the volcano.

Sustained atmospheric disturbance with a substantial pressure drop or jump → Travel speed of that air pressure wave ≈ speed of the sea waves → Proudman-like resonance → Amplified ocean waves

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha’apai Eruption

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Objectives of the study

SYNTHETIC PRESSURE WAVE MODELLING

- **Traveling Speed**
- **Amplitude functions for Peak and Trough**

PRESSURE WAVE PROPAGATION BY HYDRODYNAMIC SIMULATIONS

- **Initial circular disturbance**
- **Adjusted bathymetry with orography and temperature**

OCEAN WAVE MODELING

- **Hydrodynamic Model, NAMI DANCE**
- **Nonlinear shallow water theory**
- **Pressure forcing**

MODELLING RESULTS in 3 different regions:

Pacific, Caribbean, Mediterranean

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha'apai Eruption

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Sea level data

- The barometric measurements utilized for the amplitude and arrival time of the first and second pressure pulses collected from Japan (42 stations), Turkey (15 stations), New Zealand (3 stations) the USA (5 stations), Australia (Coober Pedy), Indonesia (Yogyakarta), Malta (Marsaxlokk), Italy (Ispra) and Germany (Stuttgart).
  - *Turkish State Meteorological Service*
  - *Automated Surface/Weather Observing Systems of National Center for Environmental Information*
  - *Weathernews Inc. Barometric pressure data by Soratena Weather Sensors*
  - *University of Malta*
  - *Indonesia: Meteorology, Climatology and Geophysical Agency*

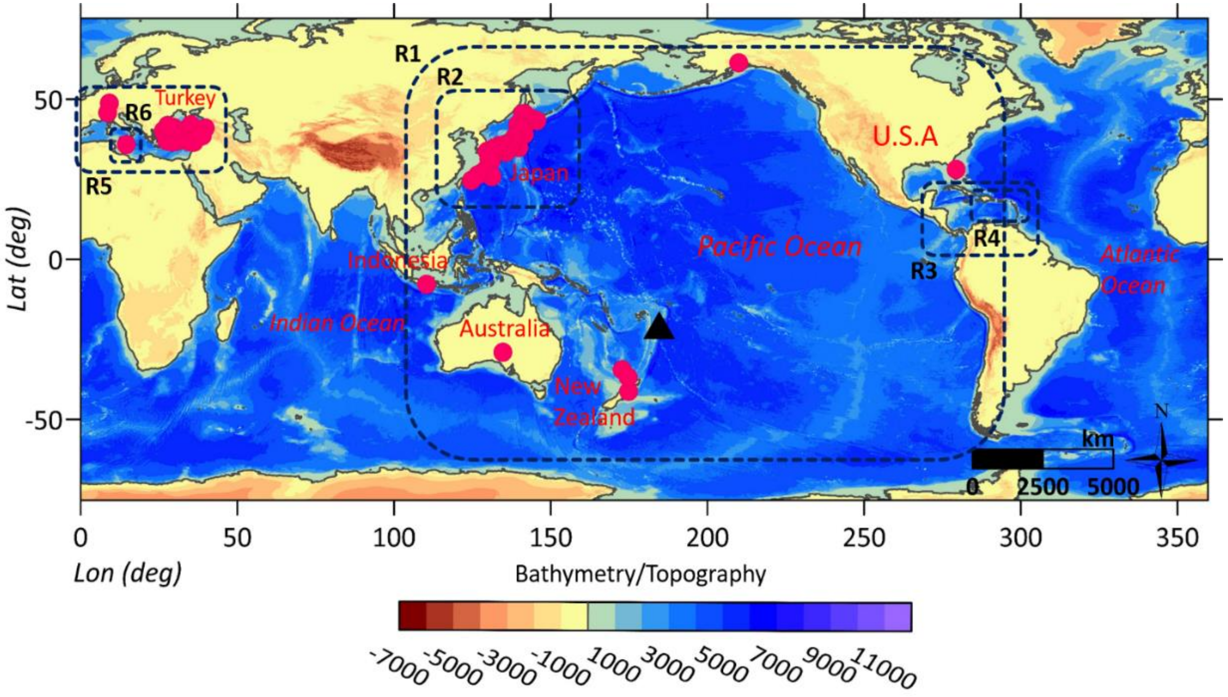

Figure 3. Stations that barometric measurements were taken from.

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Sea level data

The sea level time series used in the study were obtained from,

- *DART (Deep-ocean Assessment and Reporting of Tsunamis) buoy data form NOAA National Data Buoy Center*
- *Digitized New Zealand DART buoy data from Gusman and Roger (2022)*
- *Tide gauge records in Japan*
- *UNESCO IOC Sea Level Station Monitoring Facility*
- *European Commission World Sea Levels*

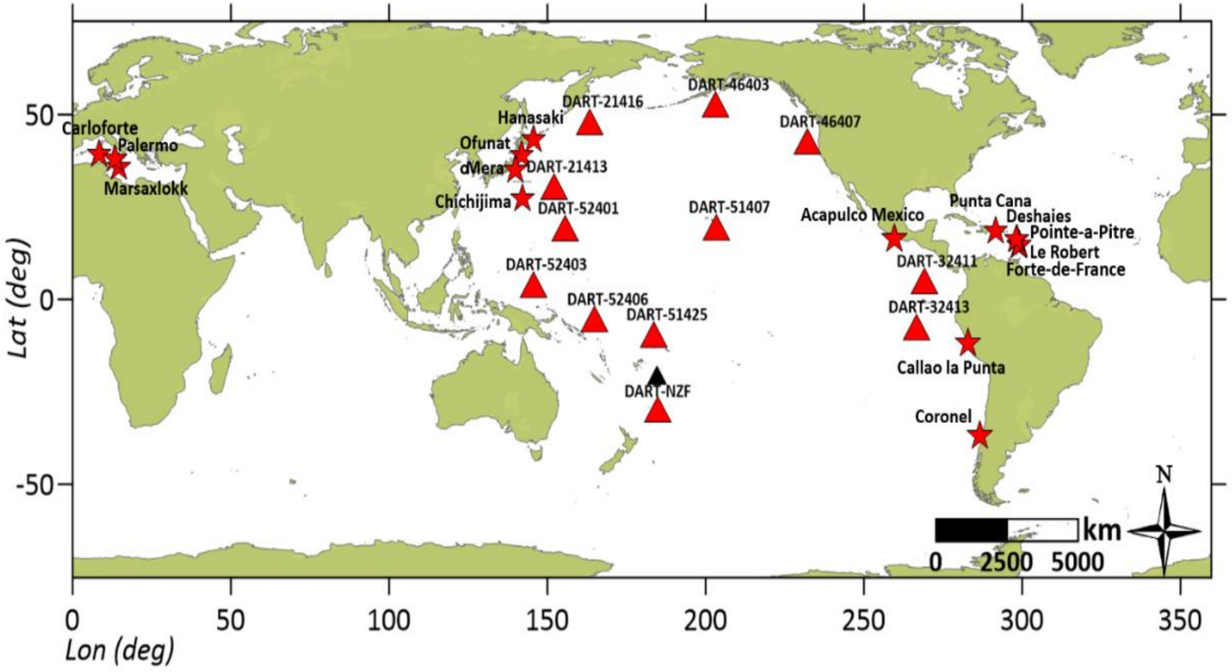

Figure 4. Numerical gauge points used for sea level comparison.

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Atmospheric pressure wave modeling

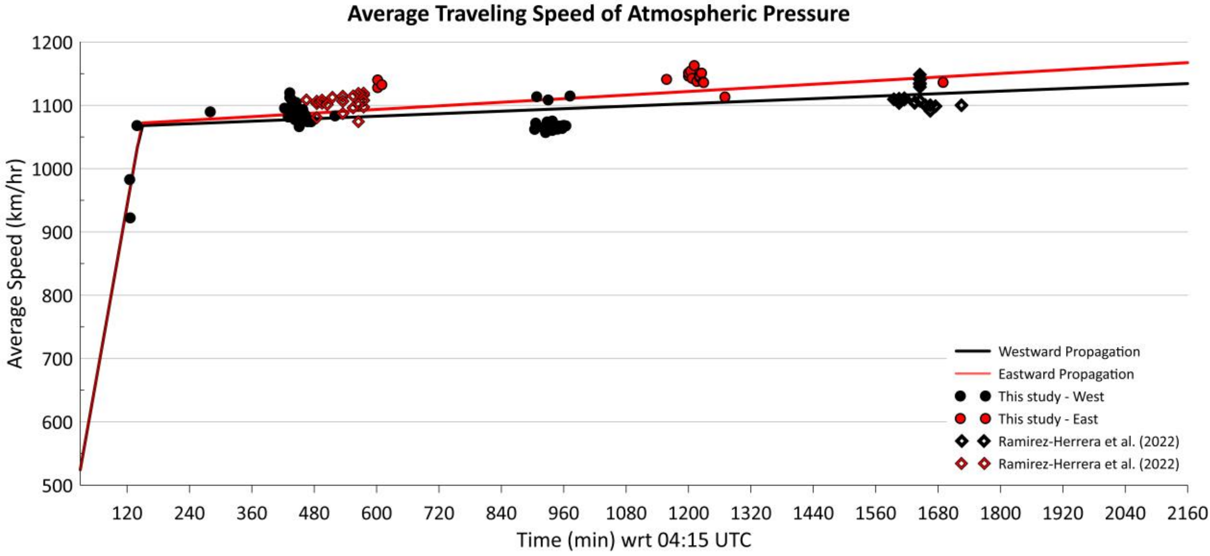
- First approach is a synthetic pressure model by empirical relationships based on the traveling speed and the amplitude of the pressure wave obtained from barometric measurements.
- Based on the arrival times and the distances of stations from the volcano, the average traveling speeds for the pressure waves were derived.
- Westward propagation is faster than eastward propagation according to measurements.
- Speed is linearly increasing but with a lower acceleration after some point, reaching a more stabilized state.

$$V(t) = 278.2*t + 385 \quad if\ 0.5 < t \leq 2.467\ hr \quad (1)$$

$$V(t) = 2.84*t + 1065 \quad if\ 2.467 < t < 36\ hr \quad (2a)$$

$$V(t) = 1.98*t + 1063 \quad if\ 2.467 < t < 36\ hr \quad (2b)$$

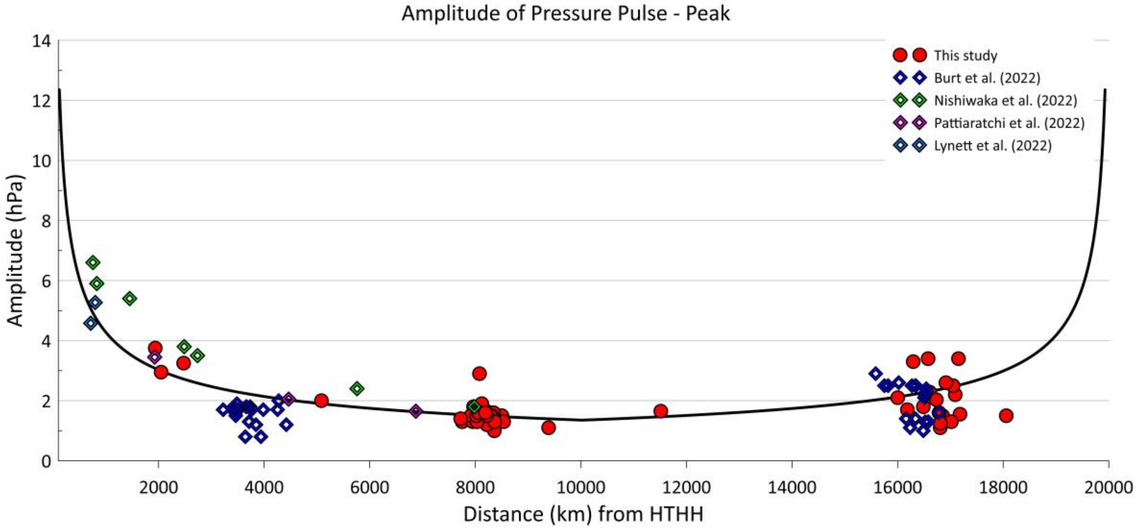
Figure 5. Linear functions of average travelling speed, (1) for the first 2.5 hours, (2a) after 2.5 hours eastward direction, (2b) after 2.5 hours westward direction.



Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha’apai Eruption

Atmospheric pressure wave modeling

- The maximum peak and trough values from the pressure time series were extracted to derive a relation for the amplitude of the pressure wave as a function of distance from the volcano.
- A power function following the pressure wave amplitude-distance analysis of Scorer (1950) was fitted to the amplitude data up to the antipodal point (~10020 km).



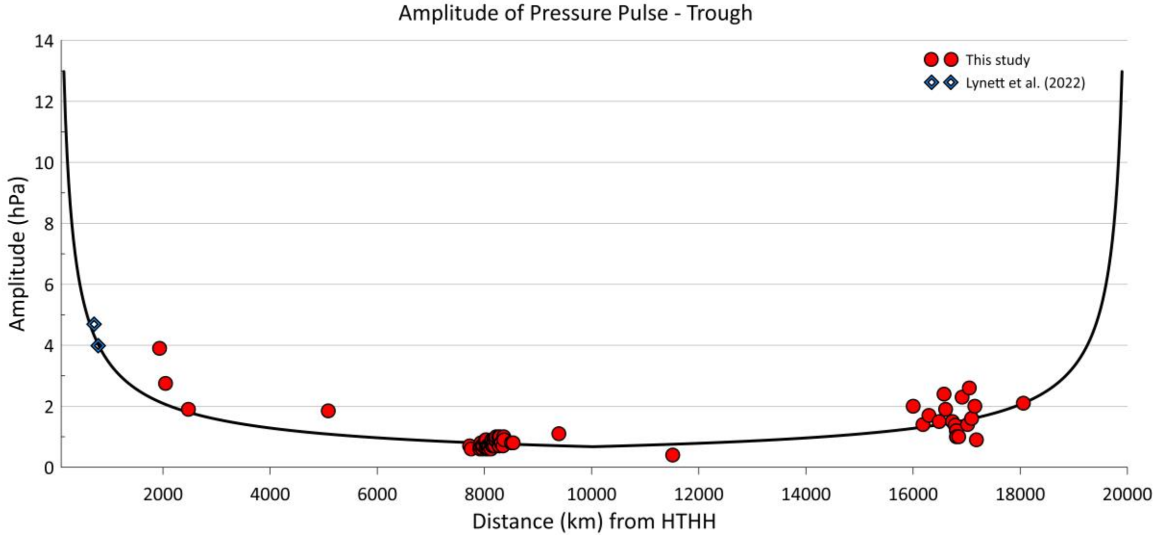


Figure 6. (b) Peak and (c) trough amplitudes of the atmospheric pressure wave as a function of distance from HTHH assumed in the synthetic model based on barometric measurements.

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha’apai Eruption

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Atmospheric pressure wave modelling – Synthetic pressure model

- Eq 3 and Eq 4 are the suggested relations for the peak and trough amplitudes of the pressure wave.
- Based on the travelling speed and amplitude relations, a sinusoidal signal with a bandwidth of 600 km was defined for meteotsunami modelling in Eq 5 and Eq 6 Williams et al. (2021).

$$a_{peak}(d) = c_{peak} * d^{c_1} \qquad (3)$$

$$a_{trough}(d) = c_{trough} * d^{c_2} \qquad (4)$$

where d=d for 0< d <πR/2, d= πR-d for πR/2< d < πR and R is the radius of the Earth

c_{peak}, c_{trough}, c_1 and c_2 are empirical constants determined as 135.3, 441.7, -0.5, and -0.7.

$$P(r,t) = a_{peak} \sin(kx) \quad if\ 0 < x < \frac{b_w}{2} \qquad (5)$$

$$P(r,t) = -a_{trough} \sin(kx) \quad if\ \frac{b_w}{2} < x < b_w,\ else\ P(r,t) = 0 \qquad (6)$$

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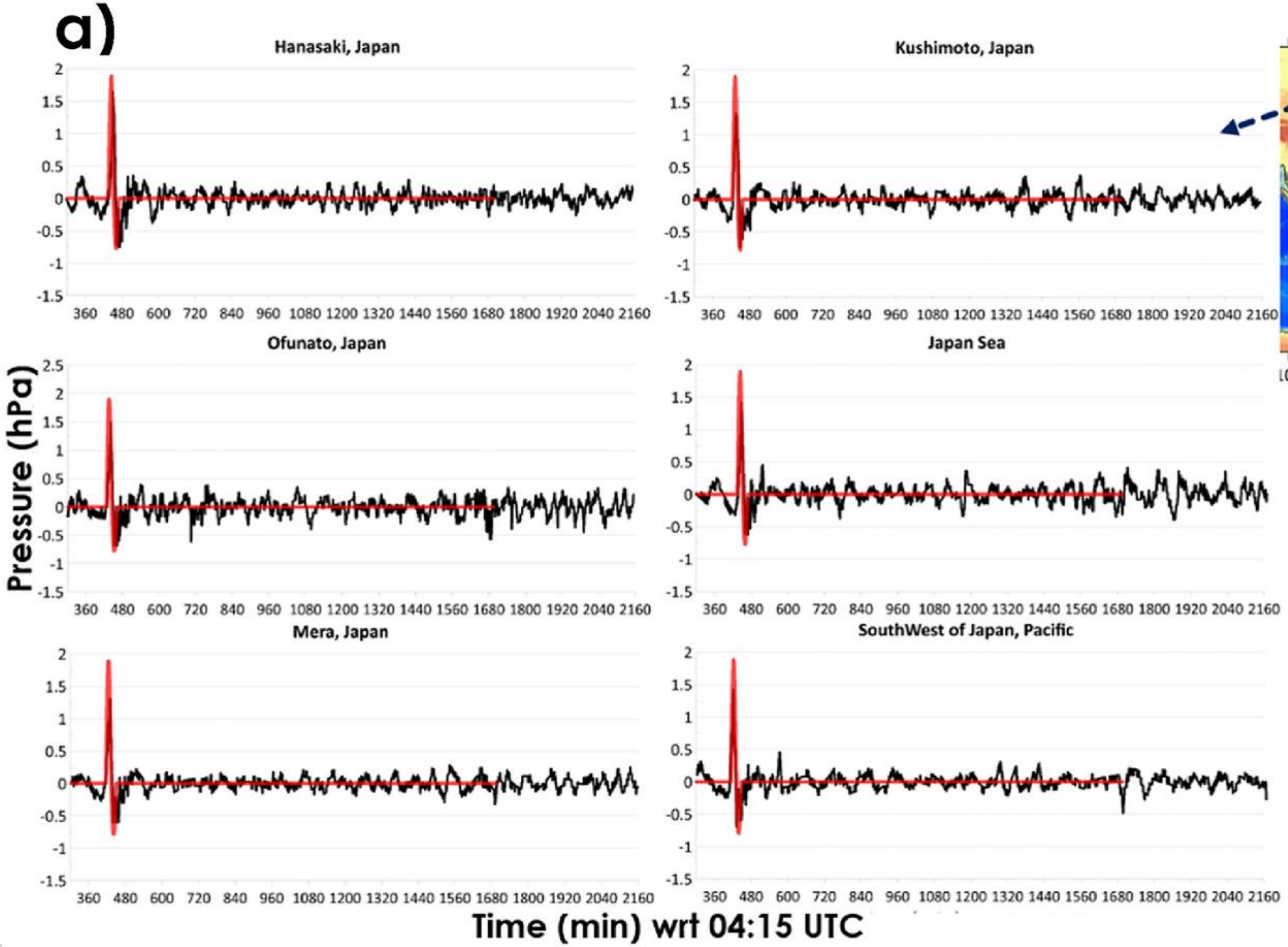
Atmospheric pressure wave modelling – Synthetic pressure model



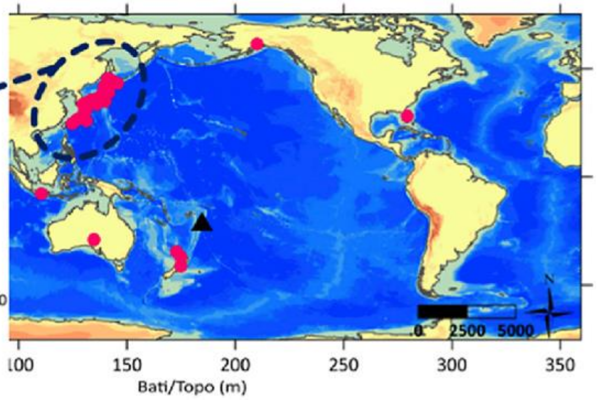


Figure 7. Comparison of pressure waves from synthetic model (red) with the measurements (black) at selected stations in Japan.

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha’apai Eruption

Atmospheric pressure wave modelling – Synthetic pressure model

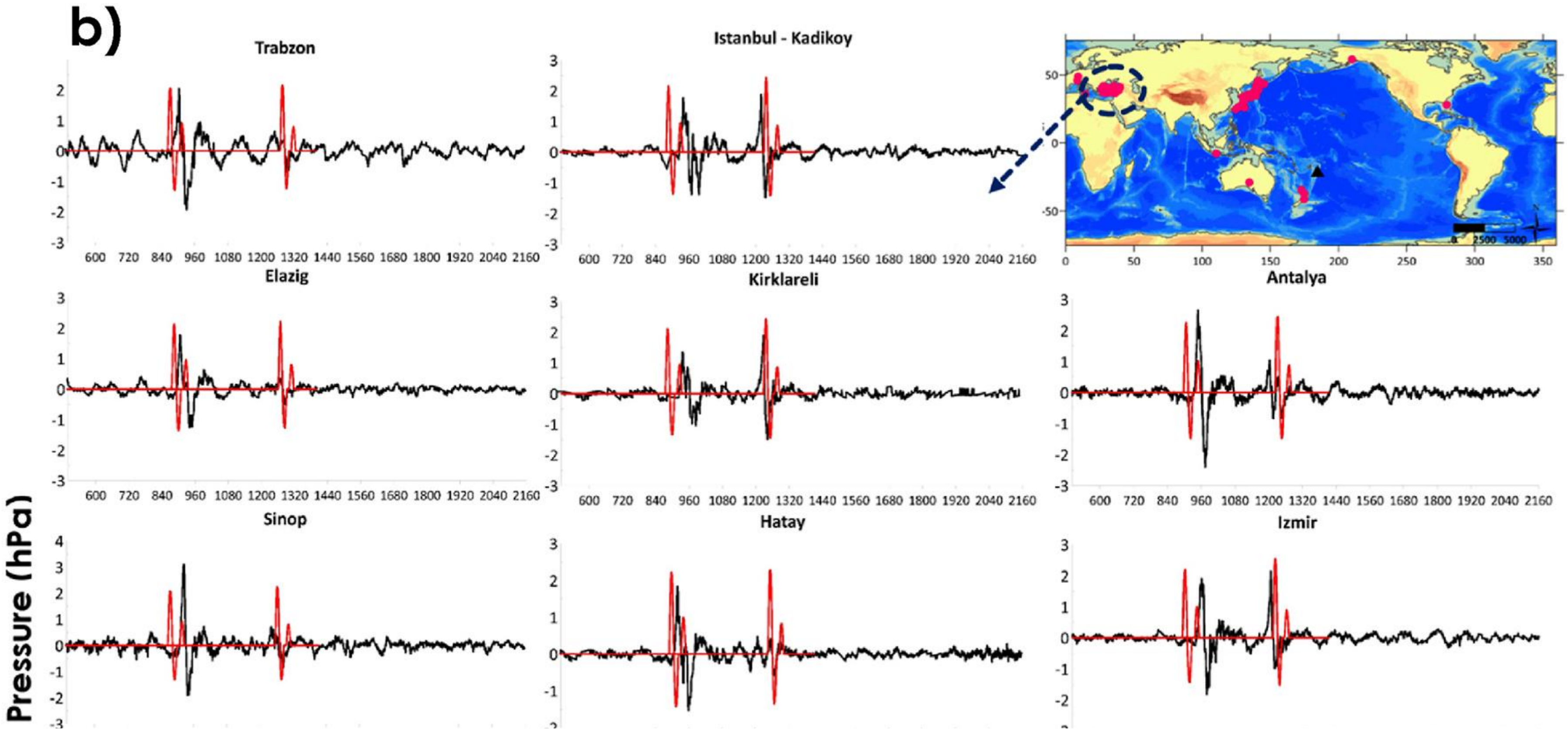


Figure 8. Comparison of pressure waves from synthetic model (red) with the measurements (black) at selected stations in Turkey.

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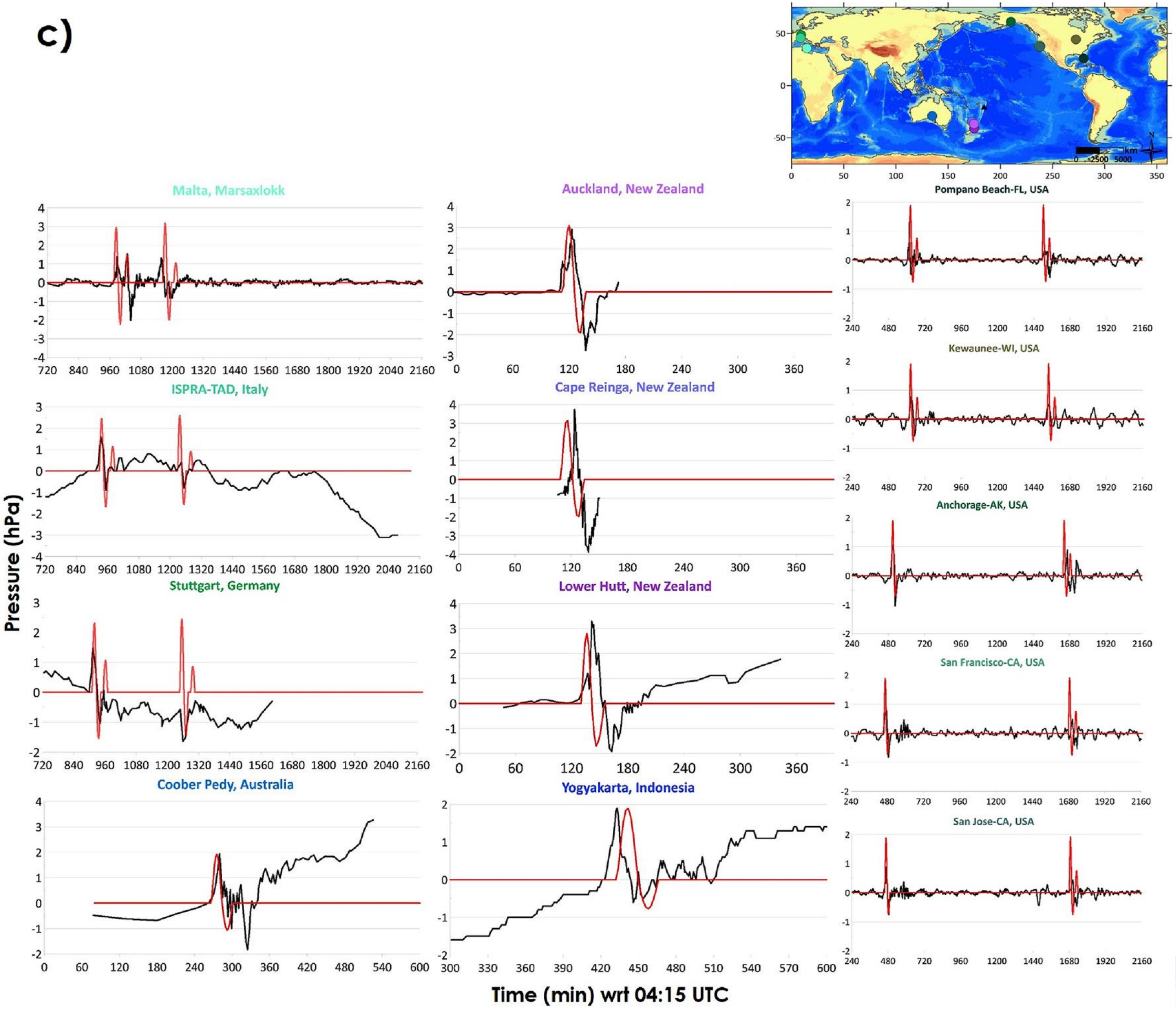

Figure 9. Comparison of pressure waves from synthetic model (red) with the measurements (black) at selected stations in several locations.

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha'apai Eruption

Atmospheric pressure wave modelling – Hydrodynamic model

- Second approach is a hydrodynamic model by NAMI DANCE Suite using non-linear shallow water theory to investigate the propagation of the pressure wave for the first cycle in different perspective.
- The atmospheric pressure waves were treated as water waves and their global propagation was simulated by using a 2D hydrodynamic model in global domain.
- Depth values are based on orography and adjusted by temperature equivalent depth values at every hour.

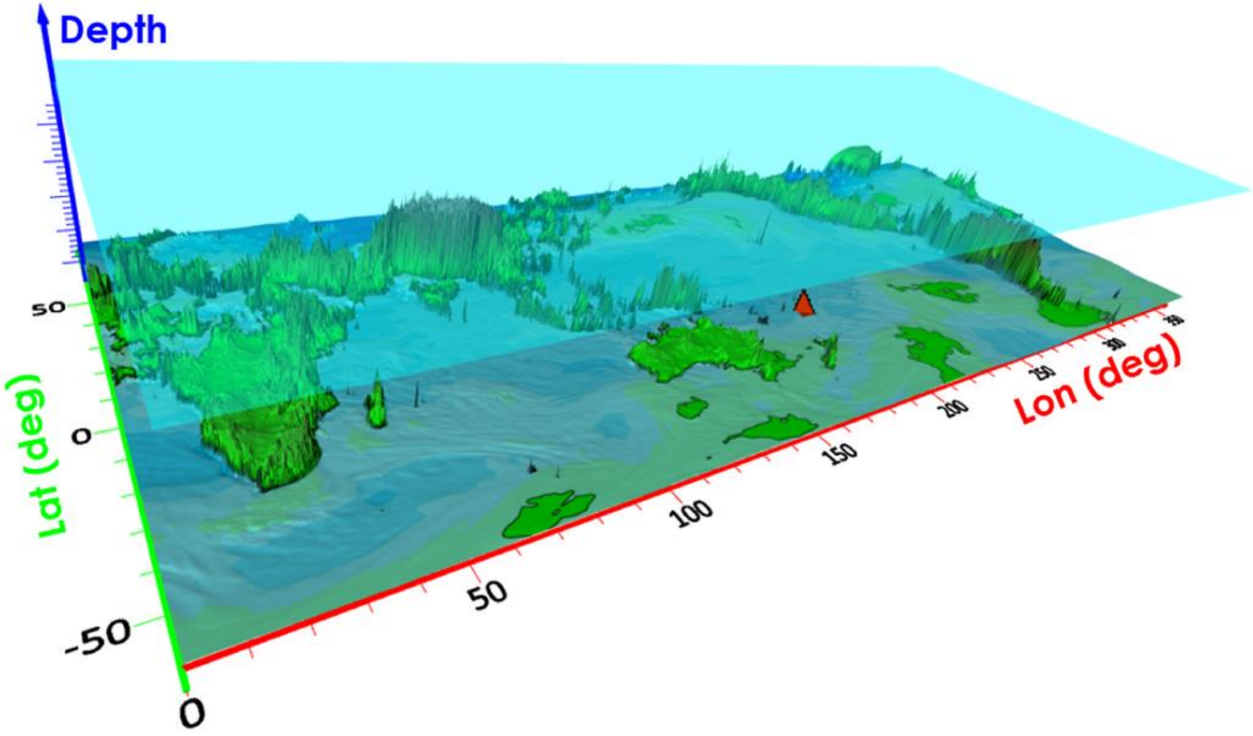

Figure 10. Schematic representation of the global domain developed for the simulation of global pressure propagation by hydrodynamic model. The red cone shows the location of the HTHH volcano.

Numerical Modelling of January 2022 Hunga Tonga-Hunga Ha’apai Eruption

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Atmospheric pressure wave modelling – Hydrodynamic model

- Assumption: The domain covering the surface of the Earth was set by assuming an initial elevation for the atmospheric pressure layer as 19.2 km on top of the sea surface and the topographic elevations were adjusted accordingly.
- Mountainous areas were the shallower areas in the bathymetry.
- Bathymetry is adjusted with temperature equivalent depth values.
  - speed of the sound wave in air $v_s = {}^{\gamma R_a T}/_{M_a}$
  - phase speed of a shallow water wave $C = \sqrt{g * h}$

$$\sqrt{g * h} = \frac{\gamma R_a T}{M_a}$$

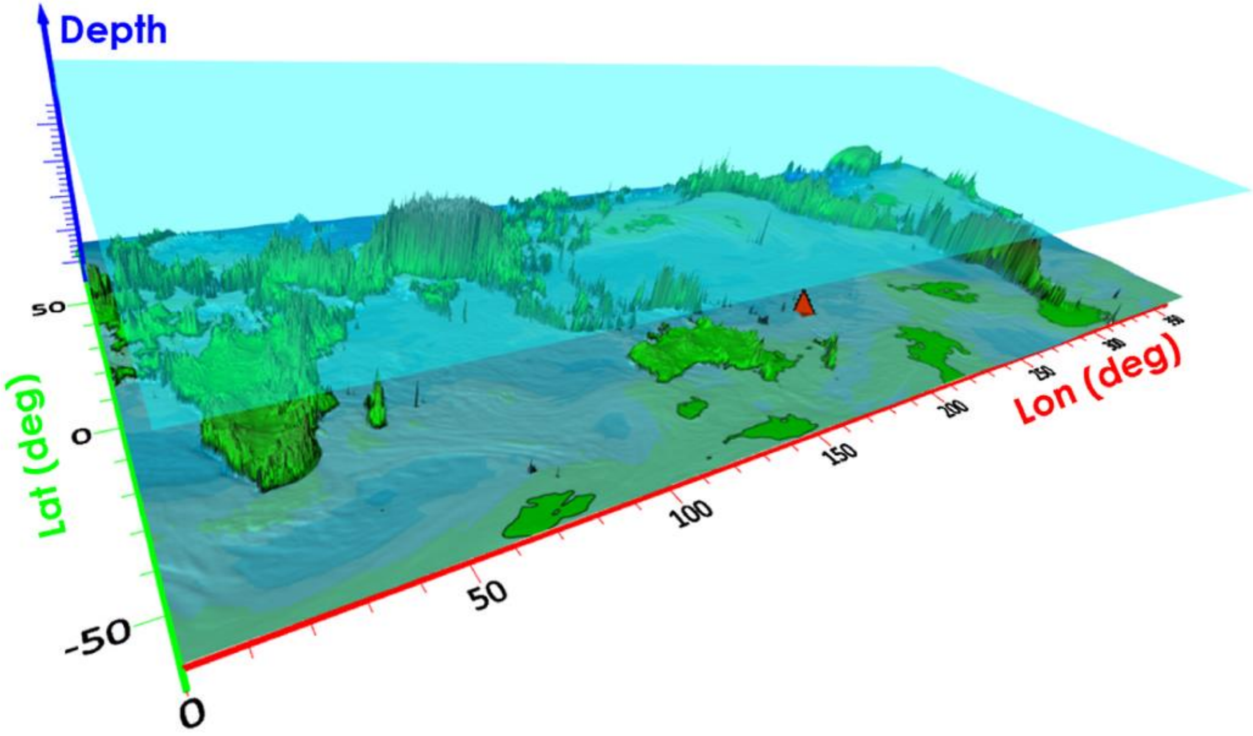

Figure 10. Schematic representation of the global domain developed for the simulation of global pressure propagation by hydrodynamic model. The red cone shows the location of the HTHH volcano.

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Atmospheric pressure wave modelling – Hydrodynamic model

- Distribution of atmospheric temperature at the atmospheric levels of 2 m and 100 hPa were obtained for every hour from ECMWF ERA5 reanalysis data and their average was taken by following the simplest approach as given by (Amores et al. 2022)
- Initial Gaussian shaped circular disturbance of 45m amplitude and 500 km diameter at volcano.
- The spatial sea level outputs of the simulation every 2 min were converted to the pressure fields and taken as an input to solve resulting ocean waves.

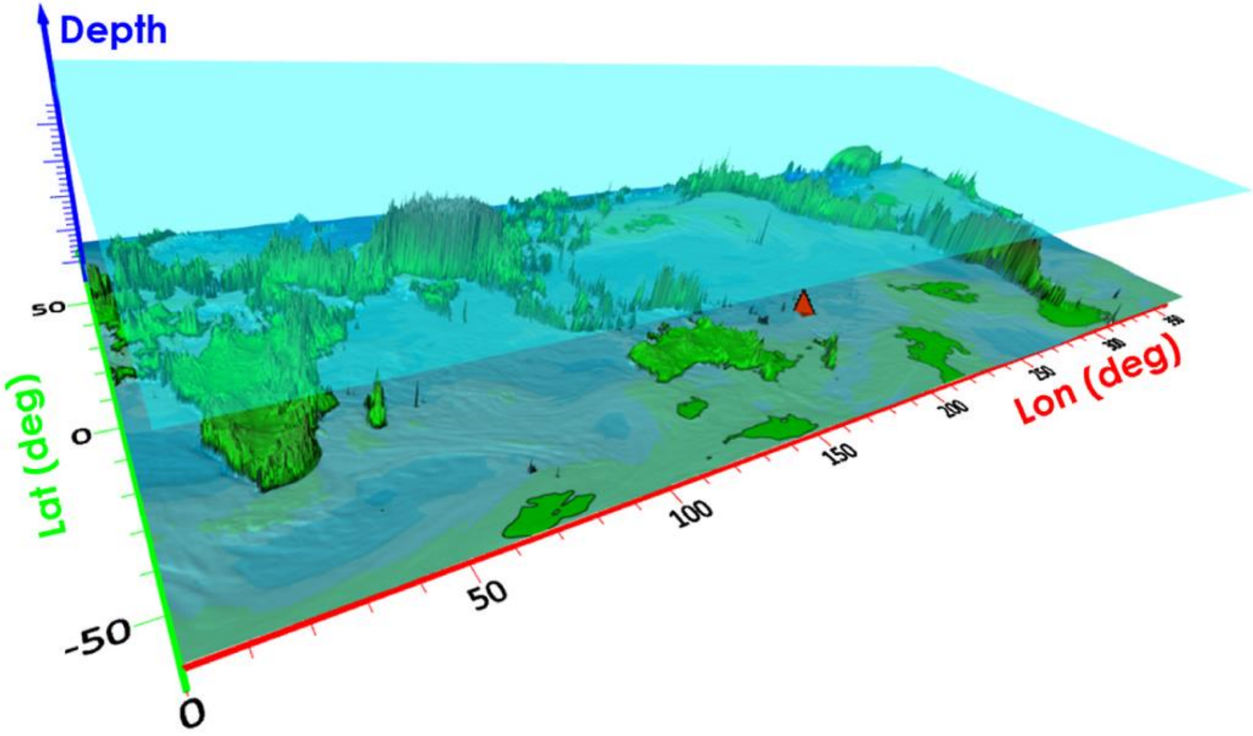

Figure 10. Schematic representation of the global domain developed for the simulation of global pressure propagation by hydrodynamic model. The red cone shows the location of the HTHH volcano.

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Bathymetry data and study domains

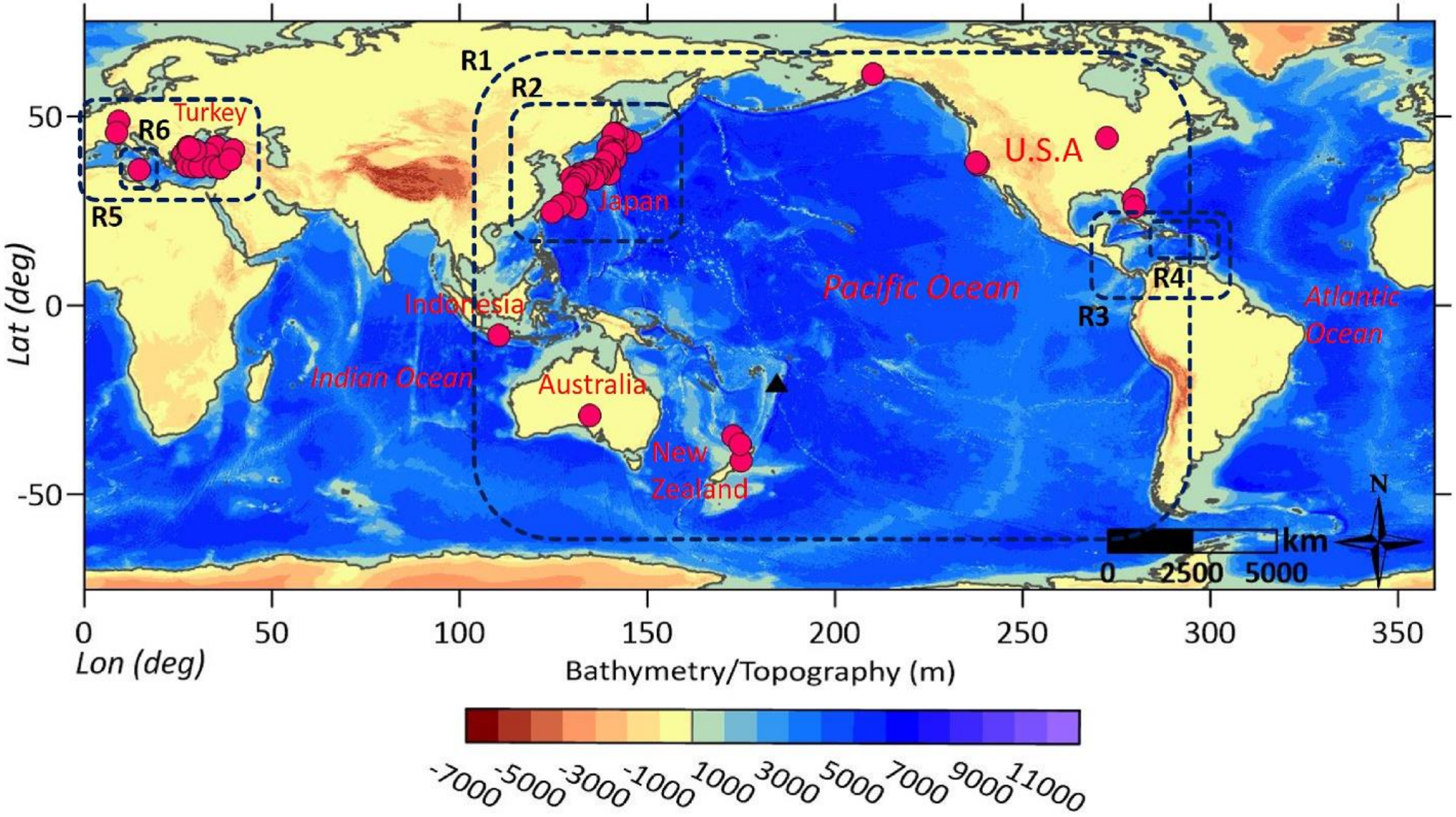

Figure 11. Bathymetry data and study domains, 6950m grid size using GEBCO 2021 bathymetry data.

R1 and R2: 3500m and 300m
R3 and R4: 600m and 240m
R5 and R6: 900m and 25m

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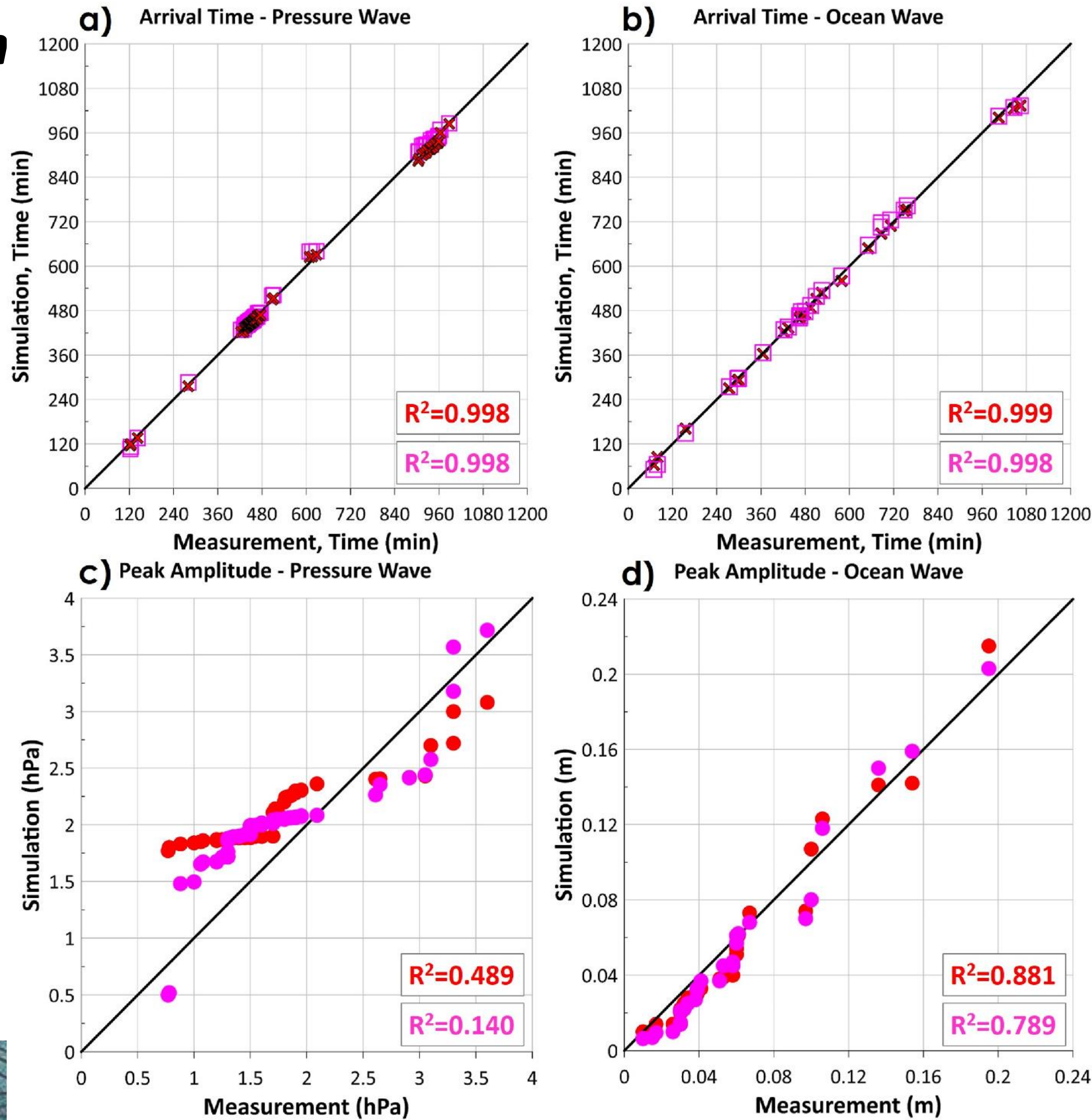
Simulation results, summary and conclusion

- Q-Q plot of the arrival time and peak amplitude of the ocean waves show that performance of the model is fairly good.
- Arrival times of the both pressure and ocean waves have excellent agreement.
- Although the peak and trough amplitudes of the pressure wave show a large scatter in 12c, speed of the wave pressure is more important to obtain observed sea levels. As shown in 12d that wave amplitudes were fairly well captured despite the low agreement in pressure wave amplitudes.



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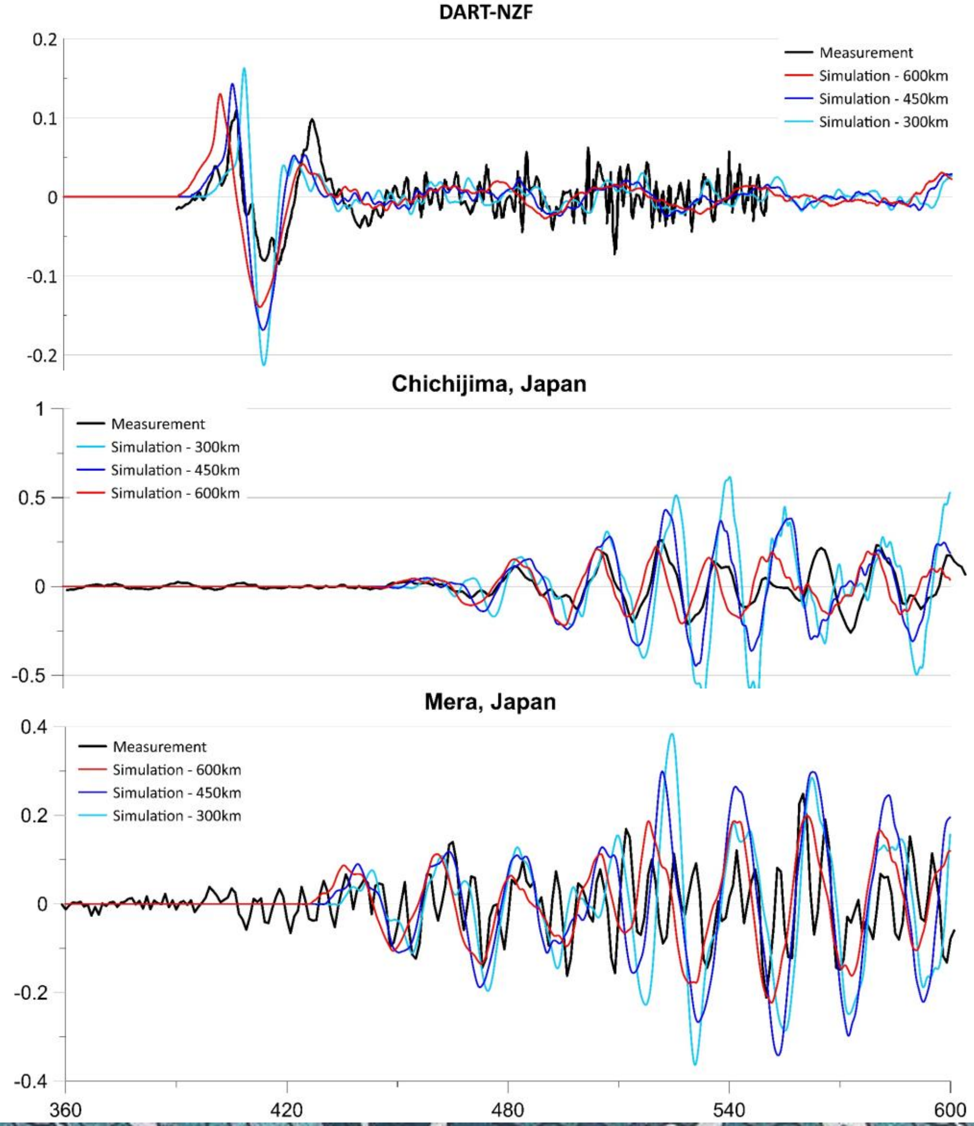
Simulation results, summary and conclusion

- Bandwidth (wavelength) of the pressure wave to be used in Haversine equations is another important parameter of the simulation shown in the figures.
- Other meteorological conditions (such as strong winds and storms, jet stream etc.) may also have distorted the pressure profiles.
- Although fine and nested domains were studied, the resolution of the sourcing bathymetry can be the negative effect of the pressure propagation discrepancies.



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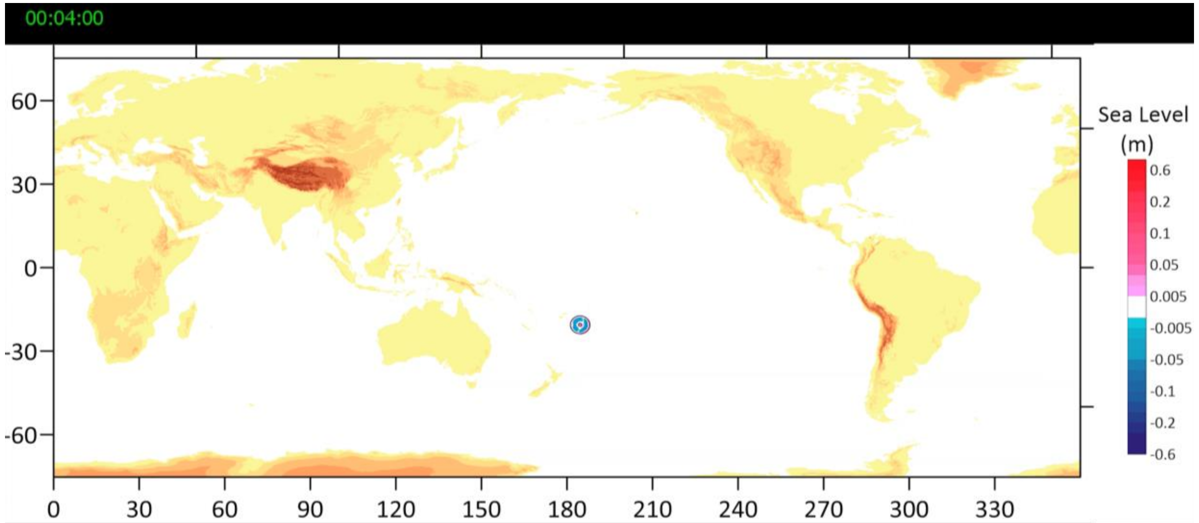
Simulation results, summary and conclusion

Synthetic Pressure Model



Hydrodynamic Model