Complex Origin of the Hunga-Tonga Volcanic Tsunami Explained by Modeling of Coastal Impact

Pacific Marine Environmental Laboratory
50 years of Science in Service to Society

Christopher Moore, Vasily Titov[1], Yong Wei[2]

[1] NOAA Center for Tsunami Research, NOAA PMEL, 7600 Sand Point Way N.E., Seattle, Washington 98115.
[2] Cooperative Institute for Climate, Ocean and Ecosystem Studies, NOAA PMEL, 7600 Sand Point Way N.E., Seattle, Washington 98115

CICOES
Cooperative Institute for Climate, Ocean and Ecosystem Studies

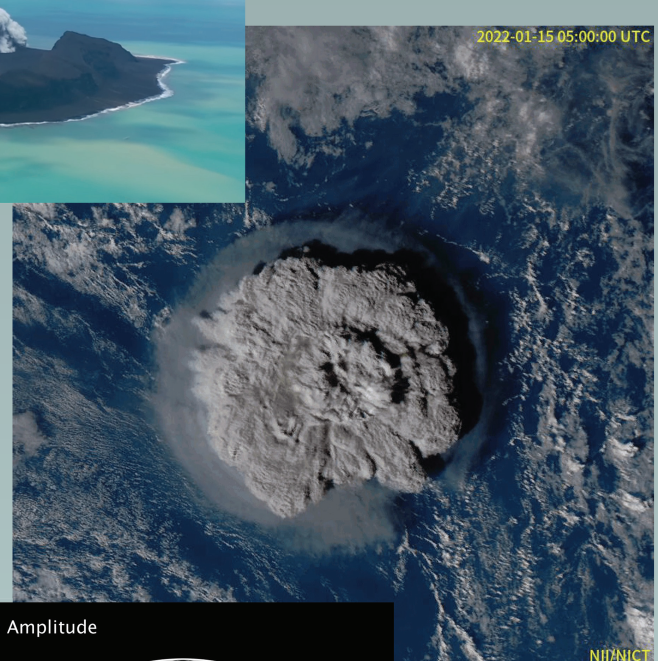
Volcanic Generated Tsunami Event

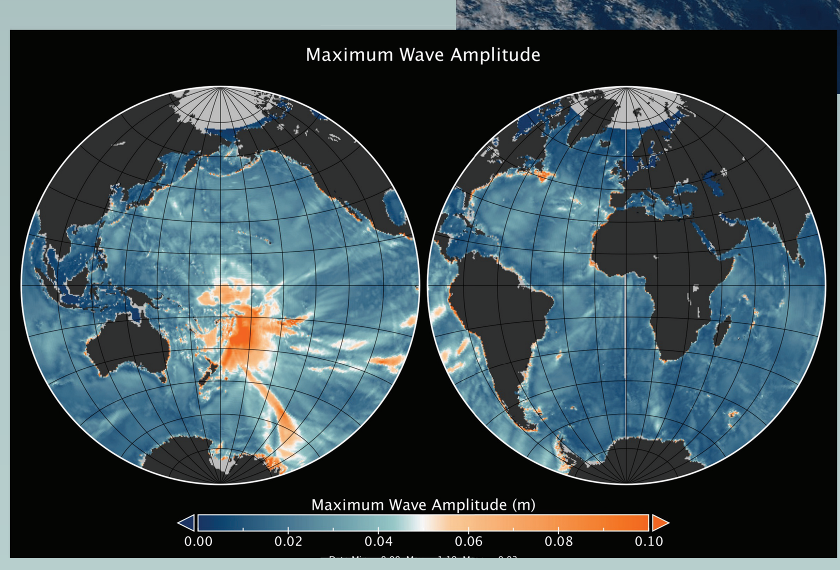
On January 15, 2022, the Hunga Tonga-Hunga Ha'apai volcano (20.5°S 175.4°W), located about 60 km north of Fua'amotu, the main island of Tonga, violently erupted with a powerful explosion, culminating the period of volcanic activity that started in December of 2021. The explosion generated a strong tsunami that was recorded all over the Pacific Ocean, the waves were also reported in other ocean basins, including the Caribbean and Mediterranean seas.

Multiple tsunami generation mechanisms were at play during this event and not all of them are currently fully understood. Research is on-going to analyze all the event data for conclusive tsunami source assessment.

The Bottom Pressure Recorders (BPRs) of the DART systems recorded the waves of the Tonga tsunami led by the air pressure waves from the volcano explosion (Figure 1). That mixture of data in the DART records complicated the tsunami analysis and source inversion process for modeling the event.

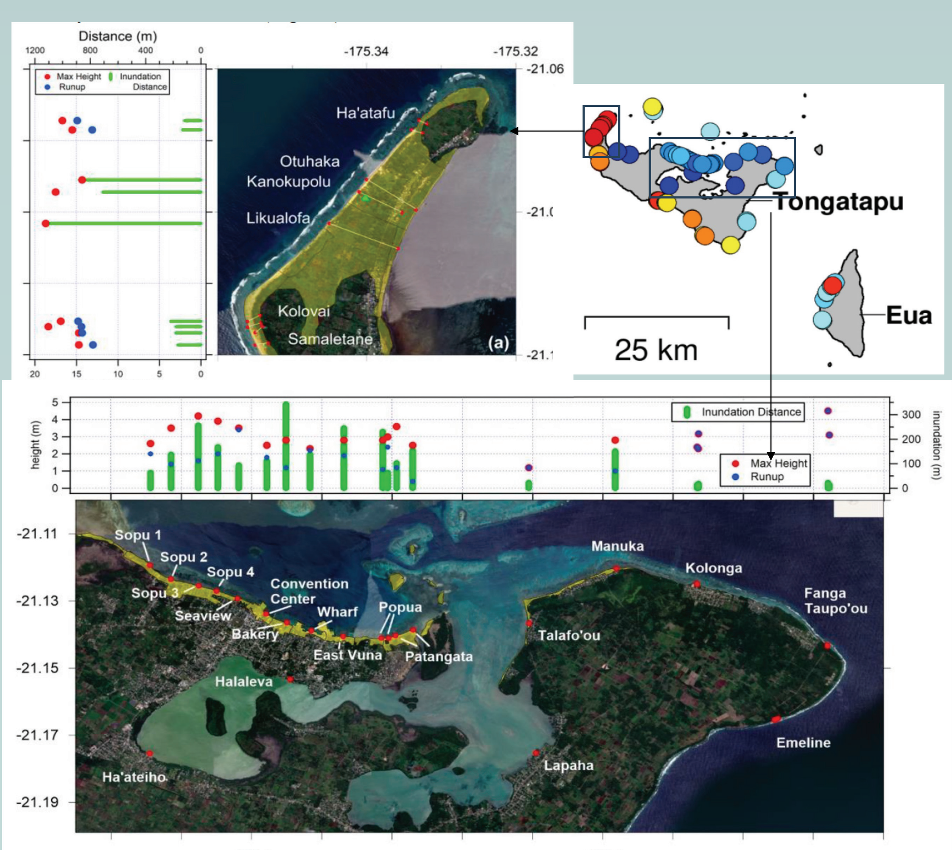
Global impacts:





Modeled max tsunami wave amplitude based on Lamb Wave

Local impacts:

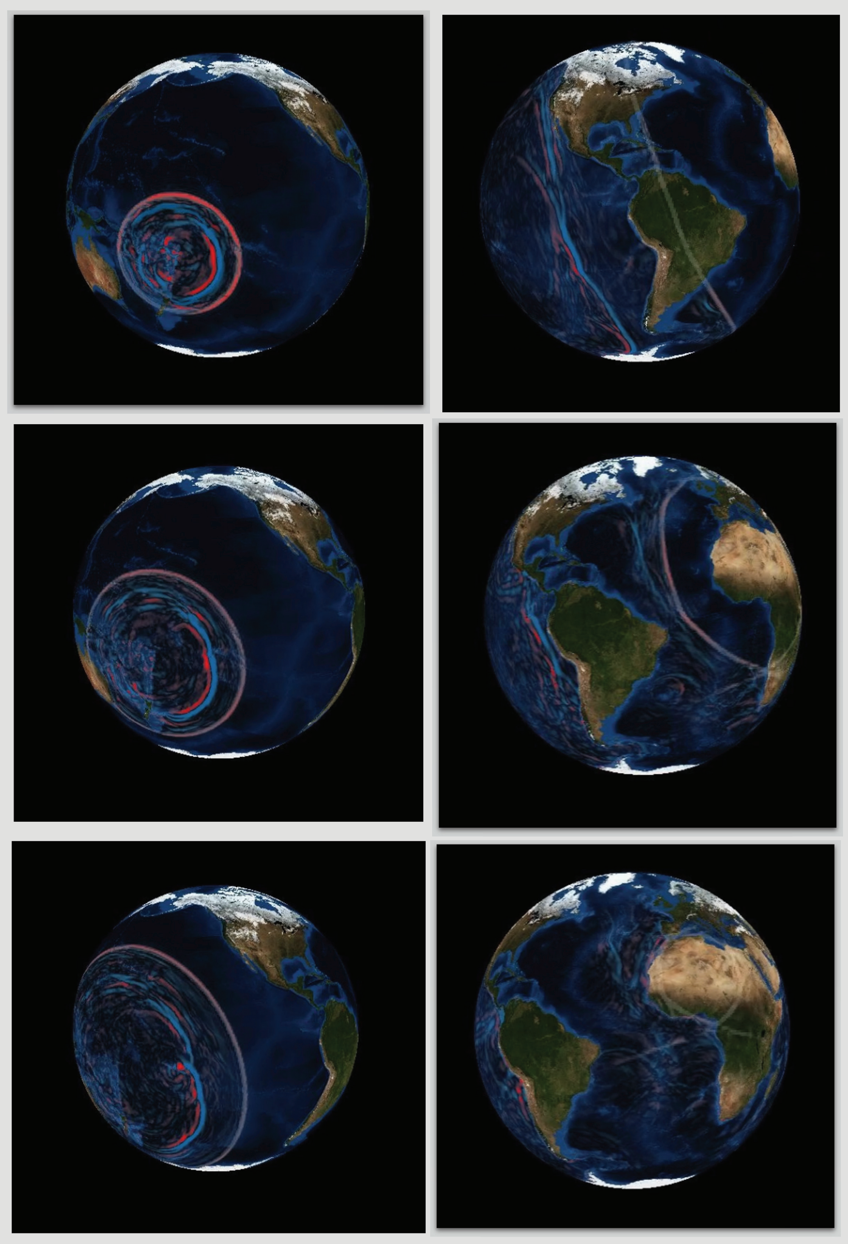


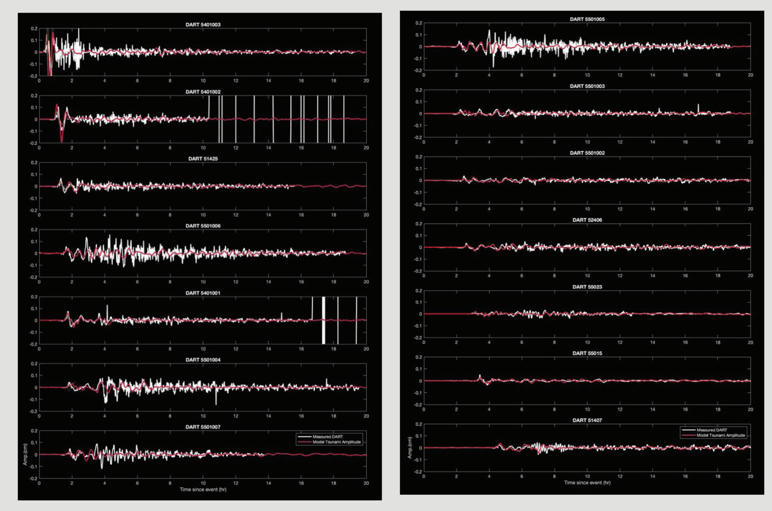
Local Impact on the island of Tongatapu. Figures are adopted from Borerro et al., (2022, PAGEOPH).

Three source mechanisms:

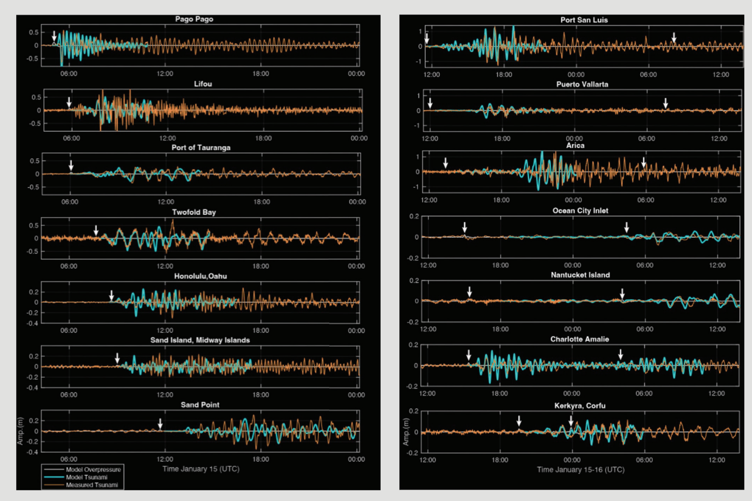
1. Lamb waves (air pressure) 2. Caldera collapse 3. Shock wave from explosion

1. Air pressure Lamb Model – wave characterization



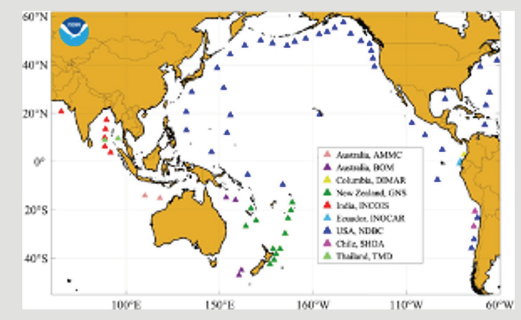


Model results based on Lamb model compared with DART observations



Model results based on Lamb model compared with tide gauge records

Tonga volcanic tsunami was detected by the global DART array

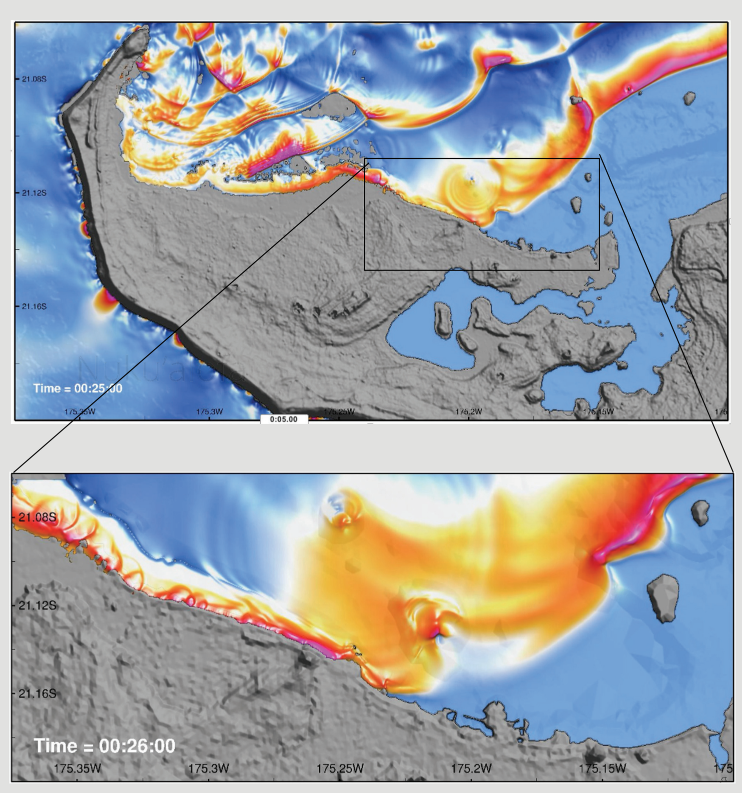


The tsunami model with Lamb wave generation mechanism explains the arrival time of the first wave signal recorded at most DARTs, which propagated just below the speed of sound in the atmosphere. It also reproduces the arrival of the following wave train propagating with the tsunami long wave celerity. Significant differences remain in amplitudes between the model and the DART observations, especially for DARTs near New Zealand and Australia. Nevertheless, the DART amplitudes in the far-field appear to be reproduced well by this simplified model. The higher-frequency tsunami signals at the near-field DARTs may have been generated by other mechanisms explained below.

2. Caldera collapse: important along Nuku'alofa's coast

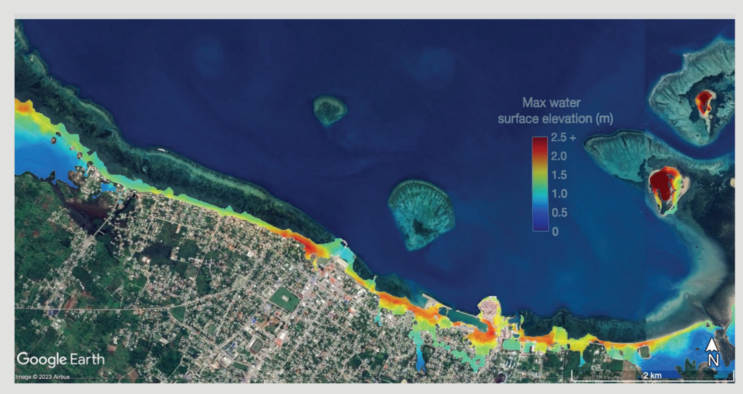
Hunga-Tonga before (left) and after (right) eruption

- Caldera collapse model is based on Pakoksung et al. (2022, *Scientific Reports*) with an explosion energy of 25 Mt (megatons of trinitrotoluene)
- Tsunami waves are simulated using nonhydrostatic NEOWAVE.
- The collapse model produces the short-period waves reasonably well at the nearest DART
- Our model shows the Caldera Collapse source plays a major role in the inundation impact along Nuku'alofa's coastline

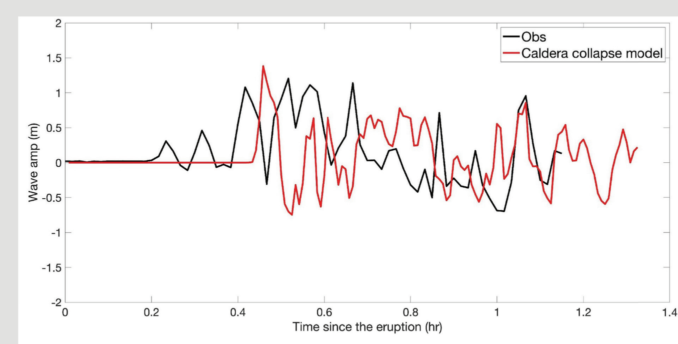


Above: Modeled tsunami wave surface elevation based on the caldera collapse model

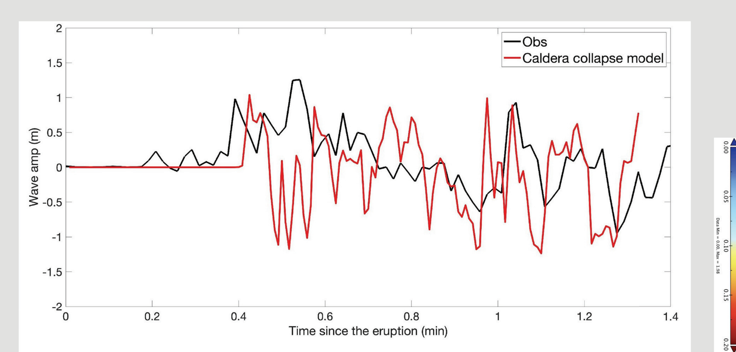
Observed inundation zone (Borrero et al. 2022)



Computed inundation zone at Nuku'alofa based on the caldera collapse model

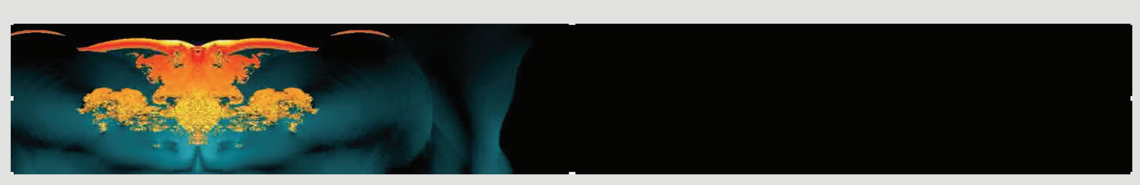


Mode/data comparison at tide gauge NKFA

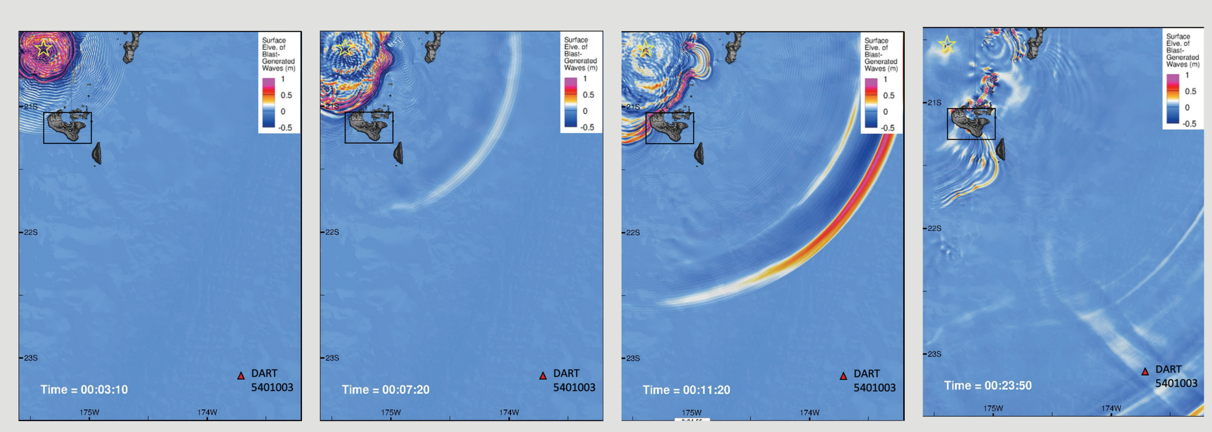


Mode/data comparison at tide gauge NKFA2

3. Shock wave from explosion



- Shock wave hydrocode simulation from 100 MT blast.
- The wavelength of the generated water waves can't match DART observations
- Wave amplitudes dissipate very quickly.
- Model shows small forerunners following the fast-moving shock front
- Larger water waves arriving at Hihifo Peninsula ~8 minutes after the eruption
- Model indicates the tsunami waves induced by the initial shock are small at Nuku'alofa



Model simulated water waves generated by the initial shock wave

Conclusions: Implications for Forecasting Volcanic Tsunamis

- Air-pressure Lamb waves dominate tsunami impact in the far field (Proudman resonance over the trench).
- Caldera collapse (maybe also landslides or pyroclastic flows) and shocks from the explosion play important roles in impacting the near field.
- DART network is particularly critical in real-time
- Model forecast calibrated using atmospheric pressure records is very effective for far-field coasts
- Equip DART with air pressure instruments for real-time model forecasting?
- Near field is more challenging

References

Borrero, J.C. et al. (2021), Tsunami runup and inundation in Tonga from the January 2022 eruption of Hunga Volcano, Pure and Applied Geophysics, 180, 1-22, https://doi.org/10.1007/s00024-022-03215-5.

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