Hunga-Tonga Hunga-Haʻapai Eruption and Tsunami: Importance of Real-time Sea Level Data for Tsunami Warning Decision-making

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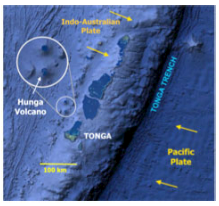
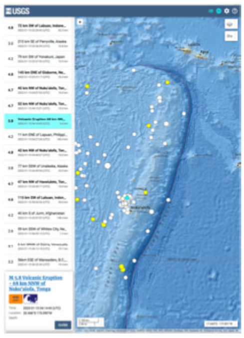
TECTONIC SETTING



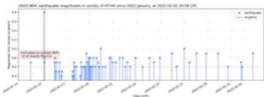
THE ERUPTION

Above left top: Hunga Tonga-Hunga Ha'apai (HTHH) volcano in the months before the 2022 eruption. *Credit: Planet Labs SkySat imagery*
Above left bottom: HTHH volcano on 18 January 2022. *Credit: ©2022 KARI, UNOSAT Processing*
Above right: The volcanic plume from the smaller eruption the day before (13 January 2022). *Credit: Taaniela Kula, Tonga Geological Services*

RECENT SEISMICITY



Left and Below: Regional seismicity (M4.5 or greater), 12 January to 12 February 2022. Eruption shown as blue diamond. Tectonic earthquakes occurred prior to and immediately after, but have been less frequent since 23 January 2022. *Credit: US Geological Survey*



ABSTRACT

The Hunga-Tonga Hunga-Haʻapai (HTHH) volcano, located 60 kilometres northwest of Tongatapu, Tonga began erupting at 407 UTC on 15 January 2022 based on Himawari-8 satellite images, with a massive explosive eruption at 0414 UTC from seismic data. The eruption triggered a tsunami that caused damage locally, regionally, and across the Pacific. The local tsunami killed three people and caused major destruction to many low-lying coastal communities on Tongatapu, ʻEua and the Haʻapai Group of Tonga; wave heights of 15 m were reported for the closest islands.

At Fuaʻamotu Domestic Airport, Tongatapu, Tonga, the eruption was first seen as an ash mushroom cloud at 0412 UTC, 15 January 2022, heard as several loud blasts, felt as a shock wave at 0421 UTC, followed by sea birds coming inland from the direction of HTHH. Based on these and the eruption the day before, the Tonga Meteorological and Coast Radio Services (TMCRS) issued an Urgent Tsunami Warning asking for immediate evacuation at 0430 UTC through a direct verbal message on Radio Tonga. The Warning was downgraded to a Marine Warning at 1248 16 January based on visual ocean observations, and cancelled at 2100 UTC 17 January 2022 for northern Tonga and at 0100 UTC 18 January 2022 for the southern Tonga.

For the event, the Pacific Tsunami Warning Center reported tsunami wave measurements from 26 countries, with the largest waves (1-2 m amplitude) recorded in Tonga, Chile, New Caledonia and Vanuatu. Many countries experienced waves greater than 0.3 meter in amplitude, which typically triggers marine advisories recommending to citizens to stay out of the water as strong currents and/or unusual waves may occur. Damaging waves struck harbours and coasts in New Zealand, Rarotonga, Hawaii and the US west Coast, and as far away as Chile in the eastern Pacific, and Japan in the northwestern Pacific.

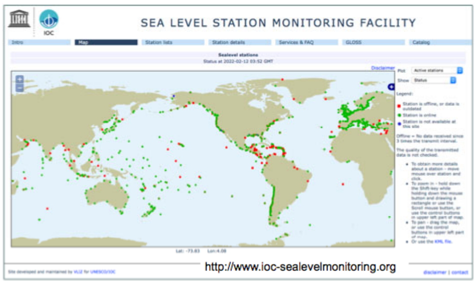
The gigantic eruption obliterated the volcanic cone-caldera complex that had grown connecting the two islands, generating an atmospheric disturbance that extended into the stratosphere and that was observed by international satellites. The multiple explosions were heard loudly not only on Tongan islands, but also in Fiji and American Samoa. The resulting shockwaves were measured on barometers as they traversed the globe. The coupling of the air wave with the ocean surface generated small waves (meteotsunamis) observed in the Pacific, and also on coastal gauges in the Caribbean and across the Atlantic in the Azores and Madeira. and as far as Cabo Verde as well as in the Indian Ocean in Mauritius.

Immediately after, the ITIC and IOC convened three Post-Event Briefs (20 January, 3 February, 10 February 2022) for Member States of the Intergovernmental Coordination Group (ICG) of the Pacific Tsunami Warning and Mitigation System (PTWS) and other stakeholders. The Briefs shared country experiences in warning and response to this atypical event, and discussed lessons learned and actions forward to strengthen their response to especially volcano tsunamis.

Nearby countries reported that in the near field, hearing of the volcanic blast sounds and social media sharing of images of the eruption and waves coming ashore in Tonga, were signals that a tsunami might come. **Countries stated that having as much real-time sea level data as possible, including the deep-ocean DART sensors, are essential as it enables them to monitor the tsunami and so make an informed decision on the potential tsunami threat to their coasts.**

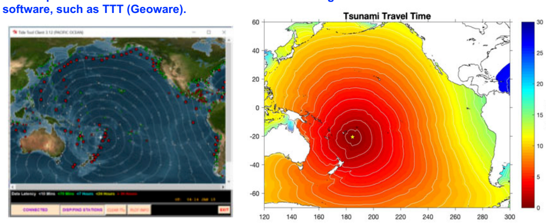
In the aftermath of the 2018 Palu and Anak Krakatau volcano near-field deadly tsunamis, the IOC TOWS Task Team on Tsunami Watch Operations established a team on atypical tsunami sources, which are all sources other than the large thrust subduction zone earthquakes that generate more than 80% of world's tsunamis and that are monitored and warned by current tsunami warning systems. Atypical tsunamis are those induced by aerial and/or submarine landslides, coastal faults that are strike-slip with horizontal motion (Palu), atmospheric conditions (meteotsunami) and volcanoes.

Tsunami Warning Centres rely on real-time sea level data to confirm the generation of a tsunami. They 'watch' different stations as the wave propagates toward them to see if it is getting smaller (and therefore won't be a tsunami threat), or getting larger (which means a tsunami warning should be issued and people should evacuate low-lying coastal areas). The more stations they have to 'watch', the better they can do to forecast the expected wave impact to their shores.

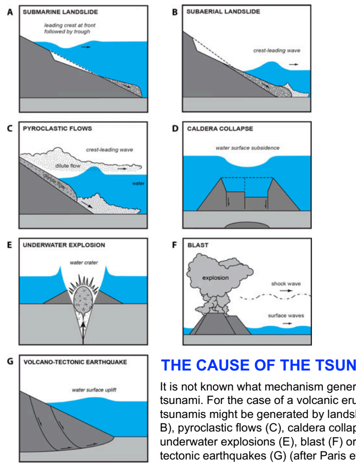


The web site provides information about the operational status of global and regional networks of real time sea level stations, including a display service for quick inspection of the raw data stream from individual stations. Stations include data from IOC programmes such as (i) the Global Sea Level Observing System Core Network; and (ii) the networks under the regional tsunami warning systems in the Indian Ocean (IOTWS), North East Atlantic & Mediterranean (NEAMTWS), Pacific (PTWS) and the Caribbean (CARIBE-EWS). At the end of 2021, about 997 active stations were tracked.

During a tsunami event, country tsunami warning centres can use the IOC Sea Level Station Monitoring Facility web site to check whether a tsunami arrived and how big it is. Expected arrival times are calculated beforehand using tsunami travel time software, such as TTT (Geoware).



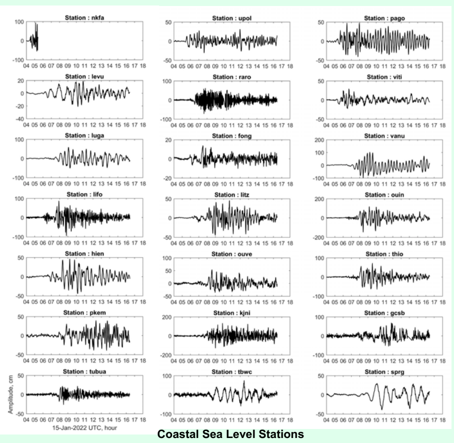
Many countries use dedicated and customized tsunami tools that automatically and continuously receive, decode, display, and analyze data for tsunamis. The PTWC and countries use the software called Tide Tool to monitor sea level stations in the Pacific, Caribbean, and around the world. The Pacific map client shows all stations received by PTWC. Small circles are coastal sea level stations and large circles are deep-ocean DART stations. Tsunami Travel Times are automatically calculated and the Estimated Time of Arrival (ETA) overlaid on each record so that it is easy to check if there is a tsunami arriving (see below for 'strip chart' example of marigrams).



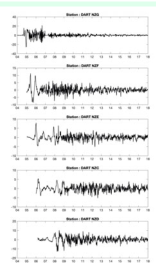
THE CAUSE OF THE TSUNAMI

It is not known what mechanism generated the tsunami. For the case of a volcanic eruption, tsunamis might be generated by landslides (A and B), pyroclastic flows (C), caldera collapse (D), underwater explosions (E), blast (F) or volcano-tectonic earthquakes (G) (after Paris et al., 2014).

TSUNAMIS IN THE NEAR- FIELD

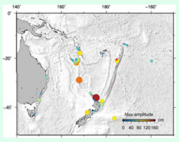


Coastal Sea Level Stations



Deep-Ocean DART

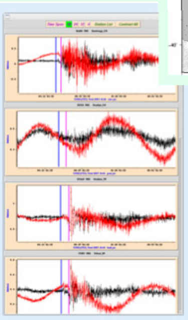
Left and Above: Waveforms recorded at coastal and DART stations in the Southwest Pacific. Below: Maximum wave amplitude recorded at coastal gauges around the South West Pacific
Credit: Gusman, A.R. & Roger, J. (2022). Hunga Tonga - Hunga Ha'apai volcano-induced sea level oscillations and tsunami simulations. GNS Science webpage, Accessed at https://doi.org/10.21420/DYKJ-RK41 on 11 February 2022



When a tsunami alarm is triggered, Tsunami Warning Centres first look at the waves of the nearest station to the source (the eruption) – this is the first indicator of how damaging the tsunami might be in the near and far field.

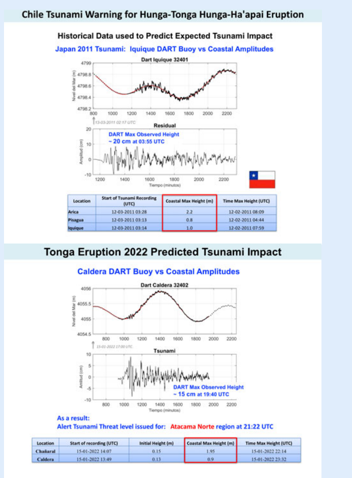
For the HTHH eruption, the 1st tsunami wave arrived at the Nuku'alofa (nkfa) sea level gauge at 0427 UTC, reaching about 1.2 m amplitude at 0447 UTC, but it stopped working at 0530 UTC. This left everyone with no data about how large the tsunami was – the signal (upper left) suggested the tsunami was getting bigger, but nobody knew.

The next instruments to trigger were the deep-ocean DART instruments, the closest being 370 km from the volcano (NZG), arrived at 442 UTC, and eventually 10 DARTs triggered, the farthest 2528 km away. **For the next 30+ hours, Tsunami Warning Centres around the Pacific monitored the sea level stations, especially those closest to them, and used the readings to judge if there was a threat, and after the wave arrived monitored until the waves were non-damaging so they could cancel advisories.**

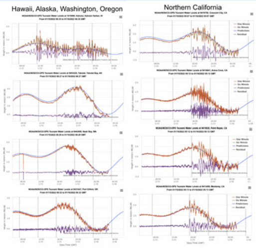


Left: Tide Tool marigrams from Cook Island and French Polynesia stations show at least two tsunami generation mechanisms at work in the far field. The magenta line indicates the usual expected travel time based on the long-wave speed of tsunamis. The blue line indicates the expected arrival time of tsunamis generated by the propagating sonic boom (sound of speed 313 m/s).
Credit: PTWC

TSUNAMIS IN THE FAR FIELD

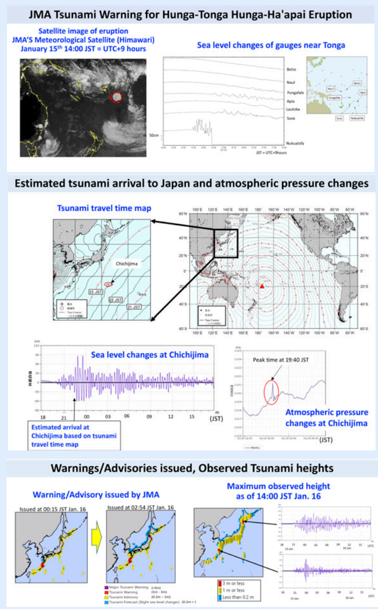


The Chile SHOA heard about the volcanic eruption but did not know its tsunami generation potential. They monitored sea level stations across the Pacific. As the wave got closer, they used DART instrument readings, calibrated from the 2011 Japan tsunami, to predict that the waves would be high enough to cause damage, and therefore issued a Tsunami Threat for their coasts.
Credit: Chile SHOA



Tsunami waves were seen across the Pacific, including Hawaii, Alaska, and the US West Coast, Tsunami advisories warned of strong currents or unusual wave action. Red marigrams are observed and purple are detided.
Credit: NOAA

The sonic boom-generated wave is seen arriving before the larger tsunami.



The Japan Meteorological Agency, upon knowing of the volcanic eruption (Himawari-8 satellite at 1400 JST, 0500 UTC) but not knowing its tsunami generation potential, monitored sea level stations in the region. They saw that the Nuku'alofa gauge had stopped working but the nearby stations only showed a very small tsunami and their evaluation was no threat (<0.2 m). At Chichijima, located 2-3 hours in tsunami travel time from the main island of Honshu, first small waves (<0.3 m, air pressure changes caused by the eruption shock / sonic-boom wave were observed) and then much larger waves (up to 0.90 m consistent with normal tsunami wave propagation) were observed. The tsunami was not a normal tsunami caused by an earthquake. Nevertheless, based on the observed tsunami heights, the JMA issued a Tsunami Warning/Advisory at 0015 JST (1515 UTC) (updated at 1754 UTC) for different parts of Japan with expected wave heights over 0.2 m in order to notify of the tsunami threat. When the wave hit, it was more than 1 m in places and caused damage to boats, but there were no casualties. *Credit: JMA*