The Hunga Tonga-Hunga Ha’apai volcano and tsunami

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Introduction

On January 15th at approximately 5:15 pm local time (0415 UTC), several weeks of heightened activity at the Hunga Tonga-Hunga Ha’apai volcano, 65 km northwest of Tongatapu (Figure 1), culminated in a violent eruption generating a massive atmospheric pressure wave and a series of tsunamis that were observed around the world. Since tsunami generation by volcanic eruptions is a relatively rare phenomenon, this event was remarkable due to the global impact of the generated waves.

On Tongatapu, tsunami waves caused catastrophic damage to the western part of the island with runup heights greater than 13 m in the Ha’atafu area (Figures 1 and 2). In the capital of Nuku’alofa media reports showed videos of waves crashing over sea walls and flooding houses, suggesting tsunami runup heights on the order of 3-5 m.

The tsunami was observed and recorded on New Zealand’s newly installed array of DART tsunameters (Borrero, 2020) located along the Tonga-Kermadec Trench subduction zone and in the Coral Sea to the west, as well as on coastal tide gauges and the GeoNet tsunami network (Figure 1).

Volcanic tsunamis

Tsunami generation from volcanic events is very complex and can involve many different processes, including evacuation of water by explosive eruptions, flank collapse (submarine or sub-aerial landslides), pyroclastic density currents entering the water (highly mobile flows of volcanic material and gas), caldera collapse and atmospheric pressure waves radiating out from the volcanic explosion.

The first four of these mechanisms can create very large and destructive tsunami waves in the near field. However, due to their relative point source origin and the dispersive nature of the waves they generate (Hayward et al., 2022), the wave energy attenuates comparatively rapidly, which renders them mostly benign in the far field (greater than a few hundred kilometres away). The latter mechanism (atmospheric pressure waves), however, has been known to have created measurable, but generally non-destructive tsunami waves at great distances from the erupting volcano. The most well-known example of this was the 1883 eruption of Krakatau in Indonesia, which created a highly destructive tsunami in the near field (> 40 m and causing >36,000 deaths) as well as a pressure generated tsunami that was recorded on tide gauges around the world. Other researchers (Lowe and de Lange, 2000) provide evidence to support the notion that the AD 200 eruption of Taupo would have also caused a global meteorologically generated volcanic tsunami.

In general, however, volcanic tsunamis are generally not considered to be a significant far-field tsunami hazard since only the largest eruptions generate pressure waves capable of producing tsunamis with non-negligible amplitudes in the far field. Furthermore, so few events have occurred that researchers in this area have very little understanding of the likely recurrence of these events. The Tonga eruption itself is the largest eruption in the Pacific in recorded history and is thought by some to be a 1 in 10,000-year event. The specifics of the tsunamis generated from this event are discussed in more detail below.

Effects in New Zealand

On the evening of January 15th, the east coast of New Zealand was just beginning to feel the effects of ex-tropical cyclone Cody, which was forecast to pass just east of East Cape on January 16th. On what was quite

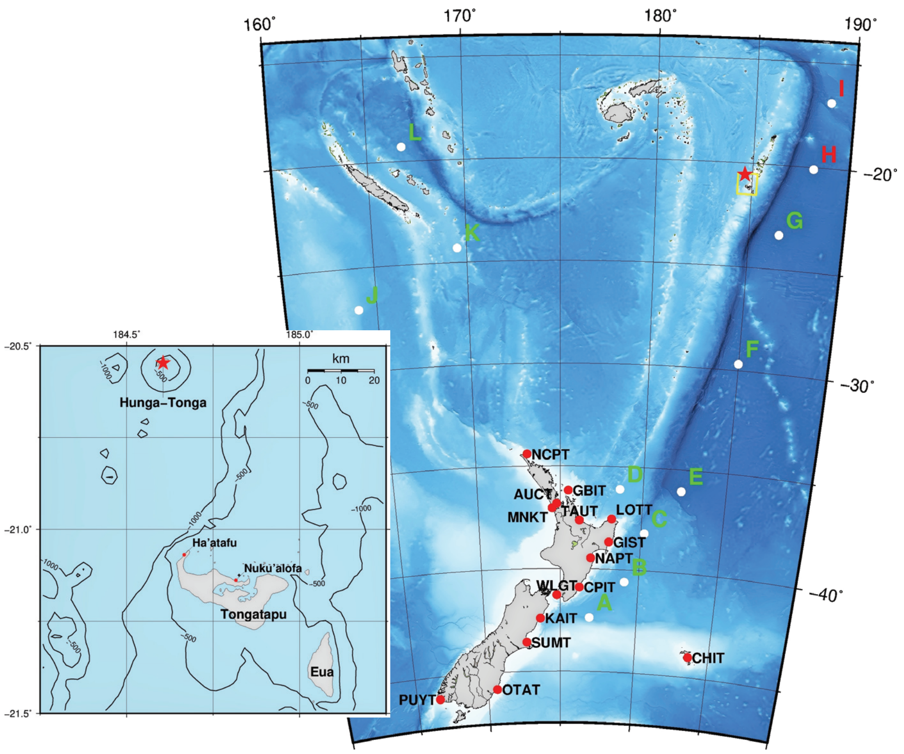

Figure 1: Location of the Hunga-Tonga volcano in the southwestern Pacific (red star), New Zealand DART stations (white dots), and GeoNet tsunami monitoring stations (red dots). DART stations in green recorded the tsunami, while stations in red were offline. Inset (yellow box) shows the location of Hunga-Tonga relative to Tongatapu and locations mentioned in the text.

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Figure 2: Tsunami damage in Ha'atafu (Photo: Moana Paea, Ha'atafu Beach Resort).

literally a 'dark and stormy' night, duty officers at New Zealand's National Emergency Management Agency were alerted to the intensification of the ongoing eruption in Tonga. Shortly thereafter NZ DART G was triggered by a tsunami wave signal and the Tsunami Experts Panel was convened to advise on the potential effects and impacts on New Zealand. Although the Panel was aware of the waves recorded on DART station G, they were hampered by a lack of quantitative information on the eruption itself. Given what was known about volcanically generated tsunami in general and the information at hand, the Panel supported NEMA's issuance of a 'Beach and Marine Threat' warning for 'strong and unusual currents and unpredictable surges at the shore' for the northeast coast of New Zealand. This warning was issued at 8:14 pm on January 15th and was in effect until 4 am on the 16th.

The most seriously affected area in New Zealand was the Northland Region, where the marina at Tutukaka was severely damaged by strong currents generated as the tsunami surge was forced through the narrow breakwater entrance. The resulting high-velocity jet was strong enough to break floating piers, including the refuelling dock, and cause boats to drift freely leading to collisions and ultimately several sunken boats (Figure 3). Also, in Northland there were reports of damage from strong currents in Whangaroa Harbour and several campsites were evacuated, although there were no reports of inundation exceeding the level of the high tide.

Water level recorders and tide gauges around the country picked up the tsunami signal (Figure 4), with some sites showing very unusual effects. The largest overall tsunami height was recorded at Great Barrier Island (GBIT) with a maximum peak to trough height of nearly 2 m occurring at approximately 1 am NZ time, some 4-5 hours after first arrival. At Wellington (WLGT) the typical resonant behaviour of Wellington Harbour was observed starting with the first arrival of the tsunami around 9 pm on the 15th. However, there was an unusual resurgence of the signal between 9 am and 2 pm the following day (20 to 25 hrs in Figure 4) with amplitudes more than double what they were earlier in the record. The Gisborne (GIST) record also showed a resurgence in tsunami energy around that time, but the largest surges were recorded earlier in the record from midnight to 3 am NZ time (11-13 hours on Figure 4). The decreases and then resurgences of tsunami energy at some of these gauges might be due to dispersive wave trains shifting in and out of phase with the local harbours and bays.

The north side of Banks Peninsula was also affected by the tsunami with a low-lying campground in Pigeon Bay being partially inundated by a tsunami surge that arrived at high tide around 4:30 am on Sunday 16th January. Le Bons Bay and Okains Bay also saw considerable erosion caused by surges traveling up their rivers and surges in Port Levy were also too strong for small craft to safely enter the water. These surges continued for several days with Cyclone Cody continuing to pump infragravity wave energy into the system set up by the tsunami.

Other far-field effects

Besides New Zealand, unusually large and persistent tsunami waves were observed on the other side of the Pacific. In Ventura Harbour California, at approximately 11 am local time Saturday (15 hours after the main eruption), a harbour patrol vessel tied to a dock was swamped and sunk as strong currents pulled on the moored vessel ultimately capsizing it. Surges persisted through the day and around 7 pm a large section of a floating dock with boats still attached broke free and collided with another vessel (*VC Star*, 16 January 2022).

Strong surges also affected coastal towns in Peru and were reportedly responsible for two drownings there after a surge hit a truck

Figure 3: Sunken boat at Tutukaka (Photo: Alec Wild, NIWA).

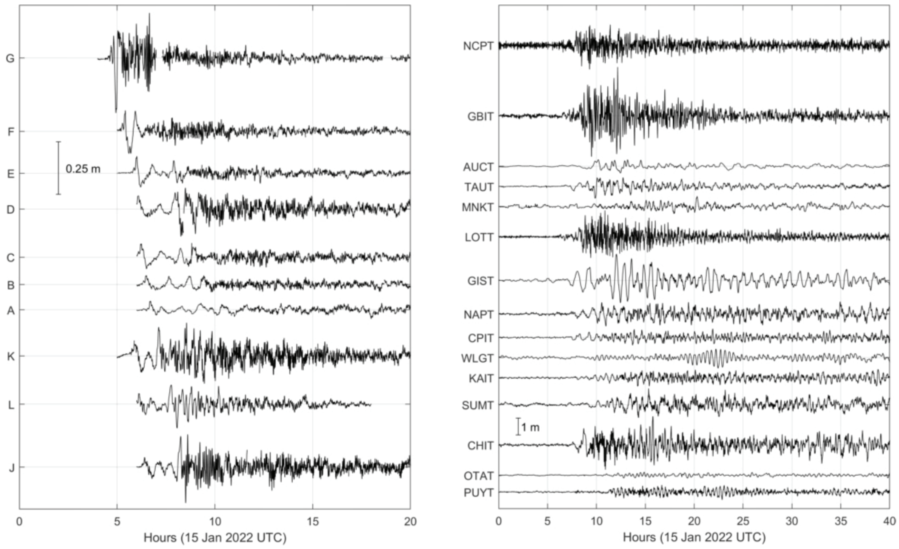

Figure 4: Records from the New Zealand DART stations (left) and GeoNet tsunami monitoring stations (right) (plots courtesy Dougal Greer, eCoast).

parked on a beach, dragging it and its occupants into the ocean (*NZ Herald*, 17 Jan 2022). The atmospheric pressure disturbance even caused measurable seiching in the Caribbean and Mediterranean Seas, although not large enough to cause problems.

Tsunami source mechanism(s) of the Hunga Tonga-Hunga Ha'apai volcanic eruption

The tsunamis caused by the Hunga-Tonga eruptions were likely caused by multiple distinct source mechanisms. According to eyewitnesses, the first tsunami waves affecting western Tongatapu arrived before the 'big bang' of the main eruption. These may have been caused by a flank collapse triggered by earlier eruptions. Later waves could have been caused by submarine caldera collapse and/or pyroclastic density currents from the collapse of the eruption column. Turbidity currents from the pyroclastic density currents may also have severed the domestic and international submarine telecommunications cables (Matangi Tonga, 2022; Speidel, 2022). More information on these sources will be available once bathymetric surveys of the affected areas are conducted later in the year, however the precise details may never be known.

Besides the waves directly caused by the eruption processes, aspects of the tsunami were enhanced or directly generated by the atmospheric pressure disturbance caused by the explosive main eruption (see Sommerville, et al. 2022). In the near field this manifested as a pressure drop of approximately 20 hPa, which radiated outwards while accelerating up to the speed of sound. In the far field (>300 km) the pressure disturbance became a dipole with a leading peak and trailing trough, which circulated around the earth multiple times travelling at the speed of sound. As this pressure disturbance moved over the ocean, it caused a deformation of the sea surface, creating a progressive long wave. When a pressure disturbance moves at speeds close to the phase speed of the water wave it is generating, an effect known as 'Proudman resonance' occurs, which results in a significant amplification of the water wave height. Ultimately, the impacts of the Hunga Tonga-Hunga Ha'apai eruption in the far field appears to be a result of the moving pressure disturbance generating tsunami waves over the ocean basins with amplification due to the Proudman effect occurring over the deeper areas. This resulted in multiple secondary tsunamis being generated over oceanic trenches as the pressure pulse circled the globe, significantly increasing the duration of the overall tsunami.

Conclusions

The eruption of Hunga Tonga-Hunga Ha'apai was an unprecedented event with no known historical analogue in the Pacific and only one other comparable event in modern history. As such, the waves generated by the event caught the tsunami warning community off guard. The resultant tsunami was generated by a complex series of events including direct wave generation (likely by a combination of pyroclastic density currents, submarine landslides and caldera collapse) as well as waves generated by the pressure pulse from the volcanic explosion propagating over the ocean.

The tsunami from this event, as well as the near- and far-field generation of tsunamis by volcanic eruptions in general, are active areas of research. The knowledge generated from the study of these topics will ultimately help to update predictive approaches currently used effectively for earthquake-generated tsunamis, allowing these to be used for the more complex source mechanisms associated with volcanic eruptions.

References

Borrero, J (2020). Tsunami-detecting DART buoys deployed offshore New Zealand. *Coastal News*, Issue 71, March 2020.

Hayward, MW, et al. (2022). Multilayer modelling of waves generated by explosive subaqueous volcanism. *Natural Hazards and Earth System Sciences*, 22(2), 617-637. https://doi.org/10.5194/nhess-22-617-2022

Lowe, D and de Lange, W (2000). Volcano-meteorological tsunamis, the c. AD 200 Taupo eruption (New Zealand) and the possibility of a global tsunami. *The Holocene* 10.3 (2000) pp 401-407.

Matangi Tonga (2022). *Torn apart, missing 110 km domestic fibre optic cable may take year to replace*. https://matangitonga.to/2022/03/01/torn-apart-missing-fibre-optic-cable

New Zealand Herald (17 January, 2022). https://www.nzherald.co.nz/world/tonga-eruption-tsunami-two-people-in-peru-drown-as-surge-hits/MX2R5NZQXI6ZU4DNNVSSRJ3ZKY

Sommerville, et al. (2022). *Why the Tonga tsunami arrived much earlier and much larger than expected.* https://riskfrontiers.com/insights/why-the-tonga-tsunami-arrived-much-earlier-and-much-larger-than-expected

Speidel, U (2022). *When volcanoes go bang, submarine cables do what?* https://blog.apnic.net/2022/03/01/when-volcanoes-go-bang-submarine-cables-do-what

Ventura County Star (16 January, 2022). https://www.vcstar.com/story/news/2022/01/16/ventura-harbor-patrol-boat-capsizes-damage-tsunami-tonga-pacific-ocean/6550000001