Terry et al. Geoscience Letters (2022) 9:24
https://doi.org/10.1186/s40562-022-00232-z

Geoscience Letters

RESEARCH LETTER

Tonga volcanic eruption and tsunami, January 2022: globally the most significant opportunity to observe an explosive and tsunamigenic submarine eruption since AD 1883 Krakatau

James P. Terry[1*], James Goff[2,3], Nigel Winspear[4], Vena Pearl Bongolan[5] and Scott Fisher[6]

Abstract

January 2022 witnessed the violent eruption of Hunga Tonga–Hunga Haʻapai submarine volcano in the South Pacific. With a volcanic explosivity index possibly equivalent to VEI 5, this represents the largest seaborne eruption for nearly one and a half centuries since Indonesia's cataclysmic explosion of Krakatau in AD 1883. The Tongan eruption remarkably produced ocean-wide tsunamis, never documented before in the Pacific instrumental record. Volcanically generated tsunamis have been referred to as a 'blind spot' in our understanding of tsunami hazards, particularly in the Pacific Ocean. This event therefore presents a unique opportunity for investigating the multiple processes contributing to volcanic tsunamigenesis. It is argued that, although challenges exist, integrating theoretical, observational, field and modelling techniques offers the best approach to improving volcanic tsunami hazard assessment across Oceania.

Introduction

Significance of the Hunga Tonga–Hunga Haʻapai volcanic eruption and tsunami

15 January 2022 saw the extremely powerful eruption of the Hunga Tonga–Hunga Haʻapai (HTHH) submarine volcano in the remote Kingdom of Tonga in the South Pacific. Producing a volcanic explosivity thought to be equivalent to VEI 5, this eruption was an order of magnitude greater than the 1991 eruption of Pinatubo in The Philippines (Cronin et al. 2022) and represents the biggest eruption of a submarine volcano for nearly one and a half centuries since the cataclysmic destruction of Krakatau in Indonesia in AD 1883. The Tongan eruption is therefore globally significant. Described by Klein (2022) as a one-in-a-thousand year event, Kusky (2022) asks whether a future possible HTHH eruption might even be able to eclipse the devastating 1650 BC eruption of Thera (Santorini) in the eastern Mediterranean. Amongst its various remarkable characteristics, Tonga's HTHH eruption generated ocean-wide tsunamis, never before recorded in the Pacific instrumental record. Although at least eight known volcanic source mechanisms are recognised for volcanic tsunamigenesis (Paris 2015; Gusman and Roger 2022), it can be said that volcanically generated tsunamis still remain a 'blind spot' in our understanding of tsunami hazards. This is particularly relevant for the Pacific Ocean because of its circum-Pacific ring-of-fire, absent in the Atlantic and Indian oceans. The Tongan event thus presents a rare chance to investigate the multiple processes contributing to volcanic tsunamigenesis, that occurred both synchronously and asynchronously with the initiating eruption.

*Correspondence: james.terry@zu.ac.ae

[1] College of Natural and Health Sciences, Zayed University, Dubai, United Arab Emirates
Full list of author information is available at the end of the article

It is appreciated that both the knowledge pool and scientific literature specific to the January 2022 HTHH eruption are rapidly growing. In spite of the fact that field-based studies in Tonga have been hampered by the global Covid pandemic, several research groups have already begun looking into many facets of the event from different perspectives, especially volcanological, atmospheric, tsunamigenic, geospatial, and numerical modelling aspects (for example Amores et al. 2022; Burt 2022; Carvajal et al. 2022; Cronin et al. 2022; Harrison 2022; Tanioka et al. 2022; Yuen et al. 2022; Zuo et al. 2022). This spontaneous surge in scientific interest is also evidenced by the dedicated scientific sessions focusing exclusively on the Tongan eruption and tsunamis scheduled at the 2022 conferences of both the European Geophysical Union (EGU 2022) and the Asia Oceania Geosciences Society (AOGS 2022), in May and August 2022, respectively. Acknowledging this groundswell of interest provides the motivation here. The current aim is to summarise some of the most prominent features of the Tongan volcanic event for science, and at the same time highlight some key gaps that can be identified in field, modelling and theoretical aspects, which are now being addressed by the scientific community.

Setting of the Hunga Tonga–Hunga Haʻapai volcano

Hunga Tonga–Hunga Haʻapai (HTHH) is one of several active volcanoes in the Kingdom of Tonga, an island archipelago nation in the South Pacific. The volcano lies at 20°32.7′S 175°23.6′W, 65 km to the NNW of Tongatapu island and the Tongan capital Nukuʻalofa. HTHH is an active stratovolcano formed as a result of westward subduction of the Pacific tectonic plate beneath the Australian plate along the Tonga-Kermadec (TK) submarine trench, an oceanic trench in the southwestern Pacific stretching between Samoa and New Zealand (Fig. 1). The trench exhibits the fastest convergence rate of tectonic plates globally, at up to 24 cm year^{-1}. All of Tonga's volcanic islands rise from the Tofua Ridge, which is a typical volcanic frontal island arc with an axis running parallel and some 150 km to the west of the TK trench (Nunn 1998).

The HTHH volcanic complex is almost entirely submarine, marked by two small islands standing on the rim of its drowned caldera (Fig. 2). The volcanic edifice rises some 1800 m from the surrounding seafloor, as seen on bathymetric maps of the region (Chase et al. 1982; GEBCO 2014). The drowned caldera is approximately 5 km across and reaches down to water depths of more than 200 m at its centre.

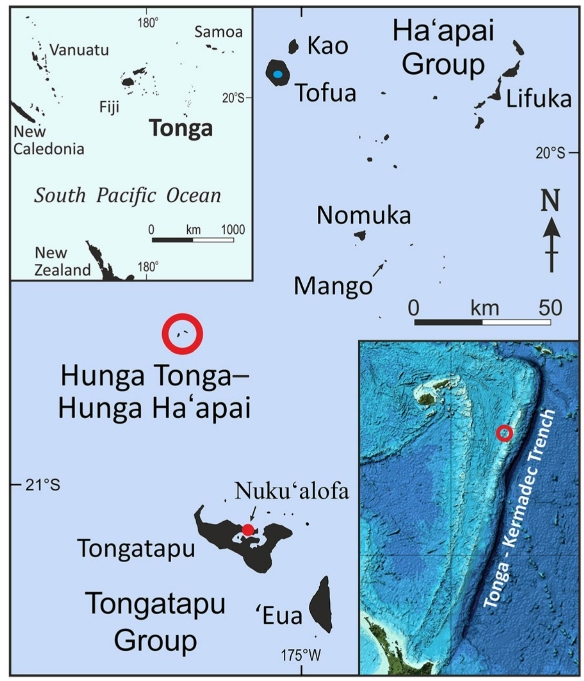

Fig. 1 Main map: location of the Hunga Tonga–Hunga Haʻapai (HTHH) volcano in southern Tonga. Lower inset image: the Tonga-Kermadec submarine trench (subduction zone) in the southwest Pacific, showing the position of HTHH volcano on the Tofua Ridge to the immediate west of the trench. Source credit for bathymetry map: GEBCO (2014)

Observations

Recent volcanic activity and eruption

The HTHH volcano has been active over recent decades (Bohnenstiehl et al. 2013) (Fig. 2). Volcanic activity from December 2014 to January 2015 was characterised by a period of constructional growth (Garvin et al. 2018; Hite et al. 2020), and was responsible for a new subaerial cone that joined separate Hunga Tonga and Hunga Haʻapai islets into a single island approximately 5 km wide. The latest phase of eruption from 28 December 2021 to 15 January 2022 is the sixth phase to be recorded since AD 1900, and was appreciably more explosive than its historical precursors (Cronin 2022).

Powerful eruptions on 14 January 2022 were of Surtseyan type. This is an explosive style of volcanism (Thorarinsson 1966) that occurs in the hydro-explosive zone within the top 500 m or so of the ocean surface (Nunn 1994), where hot magma rising rapidly interacts explosively with water (Colombier et al. 2018). Antecedent minor eruptions may have signified the magma system slowly recharging itself in advance of a big event (Brenna et al. 2022). The explosive Surtseyan-type eruptions of 14 January 2022 were likely caused by interaction between very hot (probably andesitic) magma (in

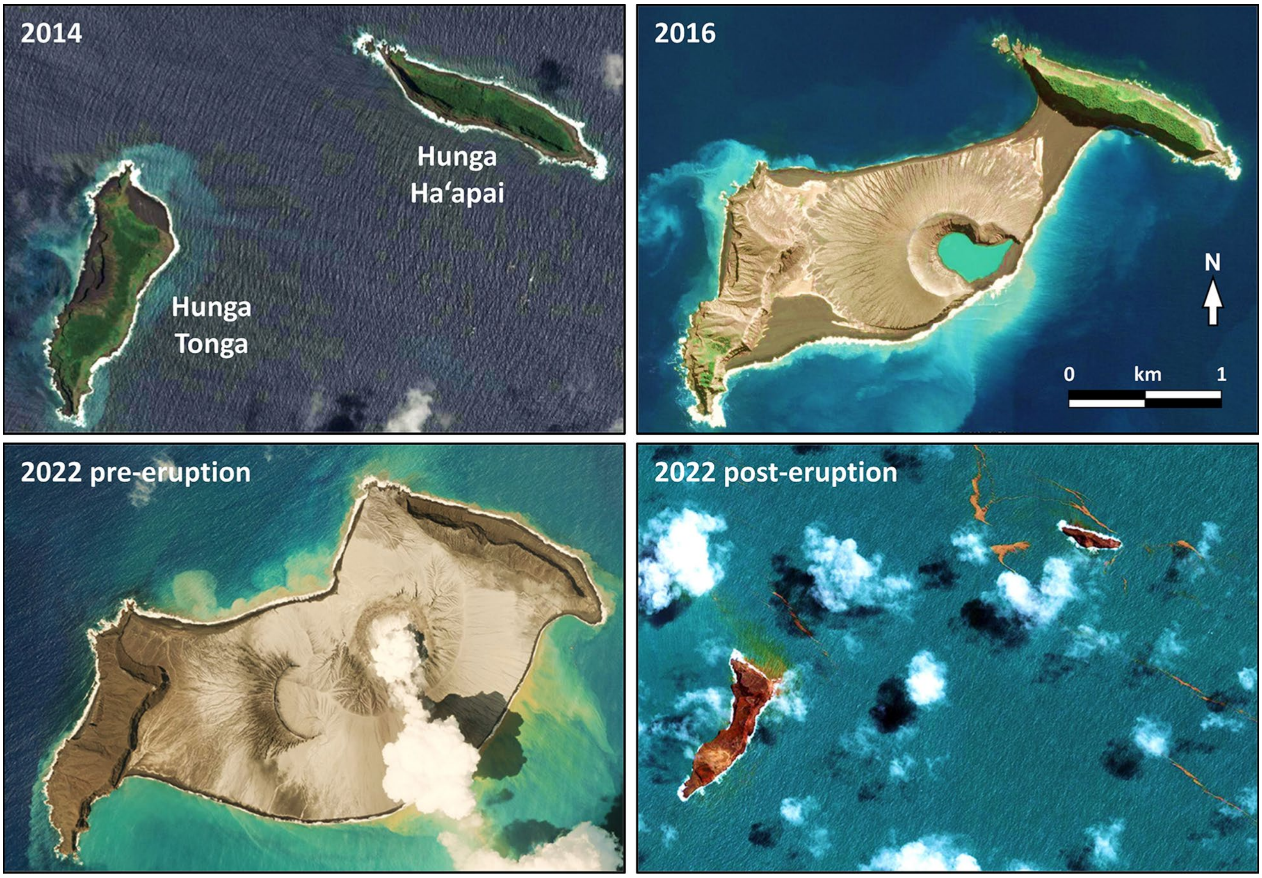

Fig. 2 Changes in the Hunga Tonga–Hunga Haʻapai volcano over time. Note the subaerial growth during a constructional phase of volcanic activity from 2014 to early 2022. Two separate islands existed on the rim of the caldera in 2014. These were connected by an eruption in 2014–2015, but subsequently disconnected and almost completely destroyed by the explosive eruption on 15 January 2022. The image in the bottom right is from 18 January 2022, three days after the most recent eruption. Credits for satellite images: CNES/Airbus and Maxar Technologies

the range 900–1100 °C) and seawater at depths of up to 150 m within the drowned caldera. Water pressure at this depth is about 15 bars, which would allow steam instantaneously generated by seawater mixing with fresh magma to boil at around 200 °C, expanding rapidly upwards as an extremely violent uprush of the resulting tephra–steam mixture, evidencing phreatomagmatic activity. Heavy ash fall was observed at the Tongan capital Nukuʻalofa.

The most violent eruptions, however, commenced the following day around 5:00 pm local time (4:00 am UTC) on 15 January 2022 (NASA 2022b; GVP 2022a; Fig. 3). The largest blast about 15 min after eruption onset was recorded as an extremely shallow earthquake of magnitude M_s 5.8 by the USGS. Thunderclap-like bangs deafened Nukuʻalofa and the thump of the explosions was heard as far away as Anchorage in Alaska on the northern Pacific Rim. Thousands of intense lightning flashes pierced the ash cloud at record-breaking rates, with more lightning created than by any other process previously recorded (Cronin et al. 2022). At least one commentator has speculated that the 15 January eruption may have reached intensity 5 on the Volcanic Explosivity Index (VEI 5 intensity) (RNZ 2022), considerably more explosive than its twentieth century predecessors that did not exceed VEI 2 (GVP 2022b). If so, the 2022 Tongan eruption would be the largest eruption globally for 30 years, since the 1991 eruption of Mt Pinatubo in The Philippines, as well as being the largest submarine explosive eruption since the AD 1883 eruption of Krakatau, between Java and Sumatra in Indonesia.

The new ash plume from this Plinian-style eruption reached well into the mesosphere, before it was distorted by upper level winds. Data from NOAA's GOES-17 and JAXA's Himawari-8 satellites were analysed by NASA scientists, who calculated that the plume rose to 58 km, thereby breaking records for the tallest volcanic plume in the satellite record (NASA 2022a; Yuen et al. 2022). The initial umbrella cloud expanded to 500 km in diameter (NASA 2022b), thereafter increasing in area to 12 million km^2 by 19 January as it dissipated downwind, reaching

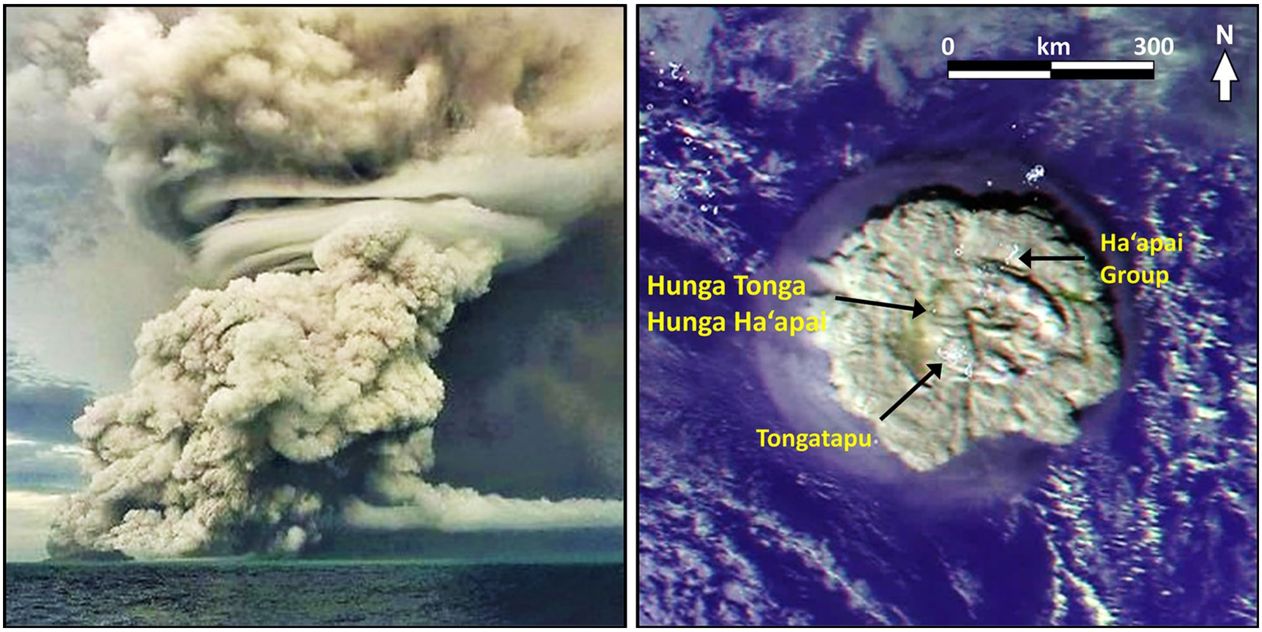

Fig. 3 Two significant eruptions of Tonga's HTHH volcano. Left: Surtseyan-style eruption of 14 January 2022, sending a large ash and steam plume high into the troposphere. Image courtesy of the Tonga Geological Services. Right: major caldera eruption on 15 January 2022. Satellite view of the expanding plume ejected. Note the off-centre position of the volcano, indicating the relatively strong (south)eastward directionality of the outward plume expansion. The central dome of the plume reached a Mesospheric altitude of 58 km. The image was captured by the AGRI (Advanced Geostationary Radiation Imager) instrument at 1 km resolution, on board the Chinese satellite FY-4B. Information available at: https://space.oscar.wmo.int/satellites/view/fy_4b. Data processed and provided by Dr. Hao Gao, China Meteorological Administration

as far away as East Africa, a distance of 15,000 km, by 22 January (GVP 2022b).

Cronin et al. (2022) believe that the enormous explosive power of HTHH's final eruption (so far) cannot be explained by the interaction of magma and water alone, and that a major caldera eruption of fresh magma highly charged with gas was responsible. Their previous age-dating work of old HTHH deposits, chemically matched to volcanic ash deposits on Tongatapu, has shown that substantial caldera eruptions have occurred approximately once every thousand years, the last around AD 1100. For the sequence of eruptions on 15 January 2022, Cronin's team (Cronin et al. 2022) have developed a hypothetical eruption model that identifies a series of distinct stages in what was clearly a highly complex multi-phase event. Initial seismic signatures are suggestive of an 'opening trapdoor' mechanism in the SE sector of the caldera that first decompressed the magma chamber. Satellite imagery shows the initial blast radiated shockwaves most strongly towards the east. Subsequent inward collapse of the caldera then rapidly squeezed out hot, fragmenting magma. This caused the most violent eruptions, destroying most of the spatial extent of Hunga-Tonga and Hunga-Ha'apai islands and cutting down their surface elevations by stripping away some 10–50 m of pyroclastic deposits. Petrology, geochemistry and glassy signatures in the poorly sorted ash are indicative of an extremely fast and complete evacuation of a heterogeneous zoned magma chamber by violent phreatomagmatic activity (Cronin et al. 2022). Perhaps surprisingly, in spite of the large volumes of gas and ash ejected, the approximate SO_2 output of 0.4 Tg (4×10^5 tons) from HTHH was modest, and is therefore unlikely to cause temporary global cooling, as otherwise experienced after the violent 1815 Tambora and 1991 Pinatubo volcanic eruptions (Zuo et al. 2022).

Volcanically generated tsunamis

The violent eruption of HTHH on 15 January generated a series of tsunami waves experienced in both proximal and far-field locations. Waves arrived first at the nearby islands of Tonga within 15–30 min of the largest blast. Dramatic videos shot by residents of Nuku'alofa and elsewhere on Tongatapu were soon posted on social media platforms. These clips captured the initial waves arriving at the coast, rushing on land and sweeping through streets and buildings. The Tongan government reported that the biggest waves up to 15 m high struck the west coast of Tongatapu, as well as 'Eua and some islands in the Ha'apai group. Drone footage posted by the Tonga Geological Services (TGS) of Tongatapu's western beaches similarly indicated that waves reached 15 m, while on Mango Island (75 km to the ENE of HTHH) runup 12 m high washed over the church tower and penetrated 500 m inland (GVP 2022c). Photographs taken during aerial reconnaissance flights by the New Zealand Defence Force revealed the extent of damage, both along affected coastlines and in adjacent low-lying areas inland. Coastal dwellings and infrastructure suffered heavy damage. Three people in Tonga sadly lost their lives to the tsunami waves. Elsewhere, tide gauges installed in ports and harbours of capital cities in surrounding South Pacific Island nations, including Fiji, American Samoa, Cook Islands and Vanuatu, measured wave heights of 0.2–1.2 m (Table 1). For the Hawaiian Islands in the central Pacific, the highest wave heights were recorded on the northern shores of Kauai (Hanalei: 0.82 m) and Maui (Kahului: 0.83 m), with tsunami deposits up to 20 cm thick reported at Kahului Harbour, at an elevation of 2 m above mean low tide and 10 m from the shoreline, overlying the carbonate sand substrate (S. Fisher, field notes).

Perhaps more remarkable was that locations thousands of kilometres distant around the Pacific Rim also experienced these volcanically generated tsunamis many hours later. Over 7000 km away in the NW Pacific, Japan recorded tsunamis along eastern coasts of both its southern and northern islands. Tsunami heights of 1.2 m and 1.1 m were observed in Kagoshima and Iwate prefectures, respectively. Thirty boats were sunk in Kochi Prefecture. Commentators noted that tsunamis arrived unexpectedly, up to 2 h earlier than predicted (Matsumoto 2022). On the opposite side of the Pacific Rim, more than 10,000 km distant from the Tongan eruption, coasts of Peru and Chile in the SE Pacific experienced 2 m tsunamis, causing two further fatalities.

Table 1 Reported tsunami wave heights for selected Pacific Islands and sites around the Pacific Rim

Country and location	Maximum tsunami (rounded) (m)
Pacific Islands	
Tonga	
Tongatapu: west coast	15
ʻEua	15
Tongatapu: Nukuʻalofa	1.2
Vanuatu: Port Villa	1.2
Fiji: Suva	0.2
Cook Islands: Rarotonga	0.7
American Samoa: Pago Pago	0.6
Hawaiian Islands	
Kauai	0.8
Maui	0.8
New Zealand: Great Barrier Island	1.3
Pacific Rim	
Japan	
Kagoshima Prefecture	1.2
Iwate Prefecture	1.1
Australia	
Norfolk Island	1.3
Gold Coast	0.8
Lord Howe Island	1.1
Peru	2.0
Chile	2.0
United States	
Southern California	1.3
Northern California	1.1

Data sources: Risk Frontiers (2022a), field observations and various internet sources (unverified)

Discussion

Possible mechanisms for tsunami generation

Submarine volcanic eruptions can displace seawater in a number of different ways, potentially triggering tsunamis. Several mechanisms are now better recognised than they have been over recent decades, although still not necessarily fully understood (Paris 2015; Goff and Terry 2016). One mechanism, however, is not completely explained, and therefore remains a challenge to interpret. These mechanisms include (1) violent volcanic eruption disturbing the sea surface; (2) flank failure or other submarine landslides around the volcanic edifice; (3) caldera collapse into the empty magma chamber post-eruption, and (4) meteotsunamis triggered by atmospheric gravity waves following subaerial volcanic blasts.

Various characteristics of the tsunamis produced by the eruption of Hunga Tonga–Hunga Haʻapai indicate that a combination of mechanisms was responsible for wave generation. The first consideration is wave size. The very large waves (up to 15 m) reported on the nearby islands of Tongatapu, ʻEua and Mango suggest that the paroxysmal eruptive blast contributed directly to the local tsunamis by displacing the sea surface upwards. For the cataclysmic AD 1883 eruption of Krakatau volcano in Indonesia (VEI 6), Pararas-Carayannis (2003) proposed that expanding gases pushed up the sea surface into a dome of water possibly 100 m high. Given that the powerful eruption of HTHH was likely of VEI 5 intensity, this effect can be envisaged in the immediate vicinity of the volcano. However, the height of an uplifted water dome, if indeed produced, remains unknown. In the absence of direct observations, hydrodynamic modelling may be the only way to investigate this scenario.

Both volcanic caldera collapse and submarine mass failures (landslides) caused by the eruption are further strong possibilities for tsunami generation. As described above, Cronin et al. (2022) believe the main eruption was a major caldera-type event, triggered by an inward collapse of the caldera following the initial eruption. The association between volcanic island edifice failures and tsunami hazards has been described by Keating and McGuire (2000). The December 2018 eruption of Indonesia's Anak Krakatau volcano caused a lateral collapse that generated a deadly tsunami in the Sunda Straits (Grilli et al. 2019; Terry et al. 2019). For the HTHH event, the undersea telecommunications cable stretching 827 km between Tonga and Fiji was broken. Internet traffic began to drop at 5:30 pm local time on 15 January 2022, but was not cut off entirely until the cable went offline at 6:40 pm (ZDNet 2022). This means that the undersea cable remained functional for more than an hour after the largest explosion, hinting at a submarine landslide that was not concurrent with the eruption, but occurred some time afterwards. Furthermore, at distal Pacific Rim sites, the biggest waves were observed on the east coast of Japan (NW of eruption) and in Peru (SE of eruption), thus implying NW–SE directionality. The tsunamigenic combination of caldera collapse and a large flank failure would be one way to account for this observed directionality, currently poorly expressed in existing models of the tsunami propagation (Fig. 4). Bathymetric surveys of the post-eruption submarine topography and restructured HTHH complex will help determine the extent of the caldera collapse, configuration of sectoral failures of the volcano, and the patterns of other slope landslides and density deposits as resulting new features.

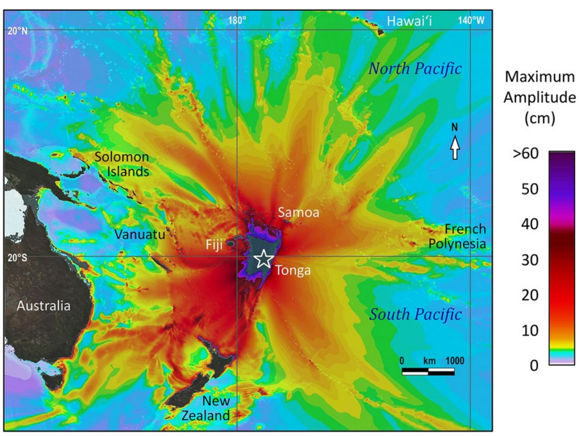

Fig. 4 Modelled maximum tsunami amplitude following the eruption of HTHH volcano on 15 January 2022. The location of the volcano in Tonga is indicated by the white star. The propagation does not include any tsunami component induced by atmospheric shockwaves. Base image courtesy of the NOAA Center for Tsunami Research (NOAA 2022)

Volcanic-meteotsunamis (VMTs) were undoubtedly generated by the Tongan eruption. Meteorological tsunamis, according to Vilibić et al. (2021), are atmospherically generated long ocean waves in the tsunami frequency band. Being driven by sudden atmospheric pressure changes (Nomitsu 1935), meteotsunamis are forced directly at the ocean surface rather than through vertical displacement of the seabed. Lowe and De Lange (2000) coined the term 'volcano-meteorological tsunami' to describe the special type of meteotsunami caused by a violent volcanic eruption. A VMT may itself be triggered by more than one mechanism. During a very powerful subaerial blast, the rapid uprush of expanding gasses and hot ash into the upper atmosphere creates gravity waves on a large scale (Adam 2022). The subsequent collapse of the gigantic eruption column can also produce similar effects (Fig. 5).

The AD 1883 Krakatau eruption in Indonesia produced VMTs that were observed worldwide, as far away as England and New Zealand. These were well studied half a

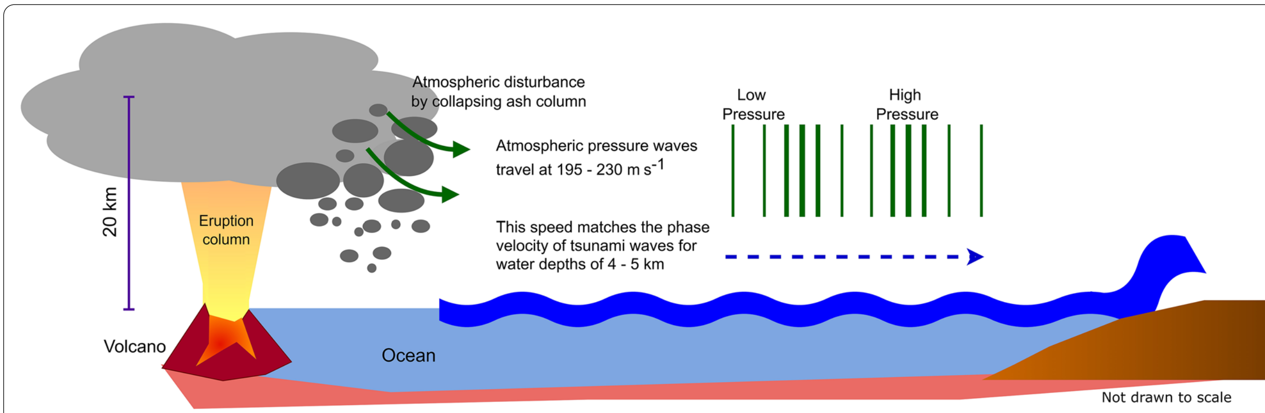

Fig. 5 Generation of volcanic-meteotsunamis (VMTs). Collapsing eruption column produces atmospheric pressure waves. If the lateral speed of the atmospheric waves matches the tsunami waves, water resonance occurs, amplifying the VMTs. Adapted from original by Lowe and De Lange (2000)

century ago. A notable observation was that tsunamis experienced far away from Krakatoa arrived earlier than would be possible for simple ocean gravity waves following all-water paths. To help explain this conundrum, Press and Harkrider (1966) suggested that phase coupling (i.e. velocity matching) could occur between atmospheric waves and long ocean tsunami waves. Advances in studying the propagation of gravity waves were becoming possible at that time owing to (then) newly available mathematical techniques (Harkrider and Press 1967). Phase coupling between the atmospheric gravity waves and the ocean gravity waves causes resonance effects. As meteotsunamis travel across deep ocean basins, Proudman resonance (Proudman 1929) is a principal type of resonance that causes wave amplification (Williams et al. 2021).

Following the violent explosions of HTHH volcano on 15 January 2022, atmospheric pressure waves (shockwaves) were seen from satellite as fast-moving concentric rings spreading rapidly outwards. These are known as Lamb waves (Lamb 1917; Amores et al. 2022). The first atmospheric gravity waves were observed across the entire planet within a few hours, and some possessed sufficient energy to circle the planet multiple times (Yuen et al. 2022). A barometric pressure jump of approximately 2 hPa was recorded globally (Burt 2022): for example at 07:30 UTC in Sydney, Australia (Risk Frontiers 2022b) and 11:00 UTC in Japan (Kataoka et al. 2022), i.e. 3½ h and 7 h after the first large eruption, respectively. On the opposite side of the planet, a 2.5-hPa pressure change was observed in Scotland after about 14 h at 18:15 UTC (Petricca 2022). In Japan, the sea surface did not respond immediately after the main pressure jump, but sea fluctuations began some 30 min later. However, the first meteotsunami wave to arrive is not the largest, because energy transfer from the atmosphere to the ocean continues. Dynamic ratios following the AD 1883 Krakatau eruption, defined as the ratio of displacement to pressure at the air–ocean interface, increased for many hours after the arrival of the initial air pulse (Harkrider and Press 1967). With reference to the Tongan event, Proudman resonance, shoaling over the continental shelf and harbour resonance were all important influences amplifying the VMTs experienced in Japan, which continued for several hours on 15 January (Sekizawa and Kohyama 2022). Thus, at distant Pacific locations, the fast-moving atmospheric pressure pulses radiating outward following the huge volcanic explosions were responsible for the leading tsunami waves, whereas the larger waves observed later were those that propagated Pacific-wide from the vicinity of the volcano itself (Carvajal et al. 2022). By contrast, islands at intermediate distances in the Pacific did not experience significant waves, likely because the large localised eruption-generated tsunamis nearest to Tonga dissipated quickly, whereas the atmospheric coupling effect was not yet fully achieved to generate VMTs.

Implications

Exposure to hazard

The recent Tongan eruption event highlights several key 'blind spots' in our current understanding of Pacific tsunamis. First, while this appears to be the first historically documented basin-wide tsunami produced by volcanic activity within the Pacific, it is by no means the only one that has happened. The massive mid-fifteenth century eruption of the Kuwae volcano in Vanuatu (Nunn 2009) produced local tsunami deposits up to at least 30 m asl on adjacent islands and as far away as the Wallis and Futuna archipelago, 1500 km distant (Goff et al. 2012a). It is tantalising to speculate whether the Kuwae event was responsible for emplacing the colossal tsunami megaclasts up to 780 m^3 in size and 10 m asl on the west coast of Tongatapu (Lavigne et al. 2021), although also acknowledging that Frohlich et al. (2009) earlier highlighted possible local submarine landslide and volcanic sources along the Tofua ridge for these deposits. The full extent of Vanuatu's Kuwae event is yet to be realised, but has been tentatively traced at least as far as New Zealand (Goff et al. 2012b). When compared to the recent Tongan eruption, it seems reasonable to propose that Kuwae's resulting tsunamis were similarly basin-wide.

Second, Tonga is no stranger to volcanically sourced tsunamis, but such events sometimes seem to slip under the radar of tsunami researchers. In 2016 it was pointed out that the Tongan island of Lifuka was affected by a tsunami generated by an eruption of Tofua volcano, some 75 km to the west (Goff and Cain 2016). Two people were drowned when their boat capsized in the waves. This volcanic event has only very recently been added to global tsunami databases. In a recent tsunami hazard assessment for Tongatapu, Borrero (2021) presents useful scenarios based on subduction-zone earthquakes. Possible tsunamigenic submarine landslide or volcanic sources are not mentioned, as these were not within the project scope of the modelling performed. Indeed, little work has been dedicated to modelling tsunami scenarios associated with the multiple potential volcanic sources and seamounts scattered along the Tofua ridge. A particular challenge is that insufficient high-resolution topo-bathymetric data are available for the expansive Pacific Ocean, which are key datasets required to underpin the production of representative and meaningful numerical tsunami models. Encouragingly, however, the inclusion of volcanic-source tsunami modelling for selected volcanoes along the Tofua ridge is the focus of ongoing work being implemented by the Tongan Government through the Pacific Resilience Program funded by the World Bank.

Third, there is a tendency to default to an earthquake interpretation for tsunami events with indeterminate (unknown) sources, since volcanically generated events tend to be (mis)recorded as small earthquakes. A random selection of two years of data reported in existing historical databases were re-evaluated by Goff and Cain (2016). Re-evaluation suggested that earthquakes sources for Pacific tsunamis should be reduced from between 65–70% to between 20–30%. In contrast, re-evaluation suggested volcanically related tsunamis should be increased from none to between 40–65%. Pacific-wide comparison of mapped ignimbrites (welded tuff)—emplaced by pyroclastic flows and hot ash clouds (and therefore indicative of immense explosive volcanic eruptions in the past)—might therefore assist ongoing efforts to reassess the relative importance of volcanic tsunamigenesis.

Fourth, a problem made abundantly clear is that forecasting systems of tsunami characteristics and arrival times based only on seismic data and precalculated models are inadequate. Authorities in Columbia and Peru, for example, issued no tsunami warnings, showing that alert systems for South American Pacific rim countries need to be re-evaluated (Toulkeridis et al. 2022). This underscores the need for more sophisticated modelling for tsunamis induced by a volcanic eruption, where there are several possible energy sources in the approximate order: volcanic tremors before and after the eruption, the eruption itself, submarine mass failure, caldera collapse, and the alluring theory of resonance between atmospheric currents and the sea surface. That said, however, modelling volcanically generated tsunamis will be very demanding because the multiple contributing processes are not all fully understood. Volcanic tsunamigenesis therefore continues to represent something akin to a 'grey box' system at present, with a partial theoretical structure that needs to be supported by extensive additional data. However, huge computational resources will be required for such data analysis (Yuen et al. 2022). Furthermore, to supplement modelling, it will be important to better integrate real-time or near real-time offshore and land-based geophysical and hydrometeorological instrumentation to improve early-warning standard operating procedures. Existing tsunami warning systems prior to the Tongan eruption were not geared for volcanic-source events, but this has been recognised by the Pacific Tsunami Warning Center, now in the process of revising operating procedures and scoping the integration of hydrometeorological monitoring systems into tsunami warnings.

Risk and resilience

While this was a moderately sized volcanically generated tsunami in historical terms, the complex characteristics of the generating processes and the proliferation of volcanoes in the region indicate that such ocean-wide events should not be unexpected. As noted, it has been suggested that prehistoric events such as the Kuwae eruption in the mid-fifteenth century produced even larger waves, at least regionally (Goff et al. 2012a). Within this context it is useful to discuss the risk as well as the hazard.

It seems extremely fortunate that only three fatalities were reported in Tonga and two in Peru. It is reasonable to suggest that the enhanced volcanic activity prior to the tsunami allowed many to move away from the coastline in Tonga. Nonetheless, the loss of infrastructure and general damage was significant and indicates the exposure of coastal communities to such events. This event (volcanic eruption, turbidity currents, and tsunami) caused economic damage in the order of US$90 million or around 18.5% of Tonga's GDP (World Bank 2022). Ongoing disruptions will further impact tourism, agriculture, commerce and infrastructure activities. Over 20% of the economic damage comes from the agricultural, forestry and fishing sectors, indicating the considerable risk faced by small island states with a high degree of exposure to coastal flooding (World Bank 2022).

While yet to be quantified, the tsunami caused notable damage in other countries within the region. Fiji (Lau Group) suffered substantial damage to schools, infrastructure and fishing vessels (World Bank 2022), some New Zealand marinas particularly in the North Island saw the loss of floating docks and vessels, and at more distant locations such as Chile and Mexico there were similar reports (Manneela and Kumar 2022). Possibly the most well documented damage was reported from California and Peru. In the former, several harbours saw damage to infrastructure both in the water (e.g. floating docks), and on land (e.g. vehicles, facilities and dredging equipment). Damage in Santa Cruz Harbor alone has been estimated at US$6.5 million (Wilson 2022). In the latter, the oil tanker Mare Doricum broke its mooring ropes at the La Pampilla oil terminal, causing a polluting oil spill with subsequent environmental problems (Marine Industry News 2022).

It is evident that coastal infrastructure and communities are at undeniable risk from such events. The nature of this volcanically generated event adds another level of complexity to the tsunami hazard and risk for the region. Authorities, and by association coastal communities, were poorly prepared. However, this event provides a much needed opportunity to enhance community awareness, improve tsunami warnings, and in the UN Decade of Ocean Science for Sustainable Development (2021–2030) perhaps address key issues surrounding risk exposure across the vast Pacific basin (Manneela and Kumar 2022).

Conclusions

The implications of the explosive 15 January 2022 Hunga Tonga–Hunga Haʻapai volcanic eruption and resulting tsunamigenesis for our understanding of both historical and prehistoric tsunamis within the Pacific basin are profound. Geologists are now beginning to undertake detailed studies of the recent Tongan tsunami deposits, which is imperative before they are disturbed either by human activity or coastal change from natural events such as tropical storms. Likewise, it is important that the stratigraphy of many South Pacific stratovolcanoes be examined, focussing on those that have received scant attention to date. An essential role can also be identified for new observational and modelling techniques, to advance our understanding of how coupled atmospheric–oceanographic resonance is able to cause very long period surface water waves in locations extremely remote from the eruptive point source. Integrating findings from these different but complementary approaches will be necessary, not only to better inform our interpretations of palaeotsunamis within Oceania, but also to enhance our understanding of the regional tsunami hazardscape and potential future risks.

Acknowledgements
The authors are grateful to Dr. Hao Gao of the China Meteorological Administration for providing the processed satellite image from the Chinese satellite FY-4B. James Terry benefited from stimulating discussion with the following people: colleagues Dr. Robert Boldi and Prof. Michael Ogden at Zayed University, Dubai, and Prof. Gensuo Jia of the Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing. The early draft of Fig 5 was prepared by Mr Jose Marie Antonio Minoza, of the Department of Computer Science, The University of The Philippines Diliman. Two anonymous reviewers gave much constructive advice on our original manuscript that was highly appreciated.

Author contributions
JPT conceptualisation, data analysis, manuscript writing, preparation of figures, editing. JG data analysis, manuscript writing, editing. NW data analysis, manuscript writing, editing. VPB model analysis. SF fieldwork. All authors read and approved the final manuscript.

Funding
JPT duly acknowledges research funding from Zayed University, Grant Number R19088, and additional funds to meet publication costs.

Availability of data and materials
Any data presented in this paper, which are not already available in the public domain, will be made available on request to the corresponding author.

Declarations

Competing interests
The authors declare they have no competing interests.

Author details
[1]College of Natural and Health Sciences, Zayed University, Dubai, United Arab Emirates. [2]School of Ocean and Earth Science, University of Southampton, Southampton, UK. [3]School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, Australia. [4]CATRISX Services Ltd, Woking, UK. [5]The University of the Philippines, Diliman, The Philippines. [6]Hawai'i Land Trust, Maui, HI, USA.

Received: 16 March 2022 Accepted: 9 June 2022
Published online: 28 June 2022

References

Adam D (2022) Tonga volcano created puzzling atmospheric ripples. Nature 602:497
Amores A, Monserrat S, Marcos M, Argüeso D, Villalonga J, Jordà G, Gomis D (2022) Numerical simulation of atmospheric Lamb waves generated by the 2022 Hunga-Tonga volcanic eruption. Geophys Res Lett 49(6):e2022GL098240
AOGS (2022) Hunga Tonga-hunga Ha'apai Volcanic Eruption, Atmospheric, Ocean Waves and Solid Earth. Session IG29 at the 19th annual meeting, Asia Oceania Geosciences Society, 1–5 August, 2022, https://www.asiaoceania.org/aogs2022/public.asp?page=sessions_and_conveners.asp
Bohnenstiehl DR, Dziak RP, Matsumoto H, Lau TKA (2013) Underwater acoustic records from the March 2009 eruption of Hunga Ha'apai-Hunga Tonga volcano in the Kingdom of Tonga. J Volcanol Geoth Res 249:12–24
Brenna M, Cronin SJ, Smith IE, Pontesilli A, Tost M, Barker S, Tonga'onevai S, Kula T, Vaiomounga R (2022) Post-caldera volcanism reveals shallow priming of an intra-ocean arc andesitic caldera: Hunga volcano Tonga, SW Pacific. Lithos 412:106614
Burt S (2022) Multiple airwaves crossing Britain and Ireland following the eruption of Hunga Tonga-Hunga Ha'apai on 15 January 2022. Weather 77:76–81
Carvajal M, Sepúlveda I, Gubler A, Garreaud R (2022) Worldwide signature of the 2022 Tonga volcanic tsunami. Geophys Res Lett. https://doi.org/10.1029/2022GL098153
Chase TE, Seekins BA, Vath SC, Cloud MA (1982) Topography of the Tonga Region. Bathymetric map at 200 m contour intervals. Department of the Interior, USGS—CCOP/SOPAC, South Pacific project
Colombier M, Scheu B, Wadsworth FB, Cronin S, Vasseur J, Dobson KJ, Hess KU, Tost M, Yilmaz TI, Cimarelli C, Brenna M (2018) Vesiculation and quenching during Surtseyan eruptions at Hunga Tonga-Hunga Ha'apai volcano, Tonga. J Geophy Res: Solid Earth 123:3762–3779
Cronin S, Kula T, Brenna M, Ukstins I, Adams D, White J, Paredes J, Baxter R, Wu J, Kilgour G, Barker S, Hamilton K (2022) Insights into a large volcanic explosion: Hunga Volcano, Tonga. from https://www.youtube.com/watch?v=4N2U8h92OPI. Accessed 2022
Cronin S (2022) Why the volcanic eruption in Tonga was so violent, and what to expect next. The conversation https://theconversation.com/why-the-volcanic-eruption-in-tonga-was-so-violent-and-what-to-expect-next-175035. Accessed 2022
EGU (2022) The 15 January 2022 Hunga Tonga Volcanic Eruption–Observation, understanding and impact of large explosive volcanic eruptions. Session ITS3.6/SM1.2 at the European Geophysical Union 2022 conference, 22–27 2022. https://meetingorganizer.copernicus.org/EGU22/session/44513#Presentations
Frohlich C, Hornbach MJ, Taylor FW, Shen CC, Moala A, Morton AE, Kruger J (2009) Huge erratic boulders in Tonga deposited by a prehistoric tsunami. Geology 37:131–134
Garvin JB, Slayback DA, Ferrini V, Frawley J, Giguere C, Asrar GR, Andersen K (2018) Monitoring and modeling the rapid evolution of Earth's newest volcanic island: Hunga Tonga Hunga Ha'apai (Tonga) using high spatial resolution satellite observations. Geophy Res Letters 45:3445–3452
GEBCO (2014) World Ocean Bathymetry. General Bathymetric Chart of the Oceans, world map 2014. British Oceanographic Data Centre. https://www.gebco.net/data_and_products/printable_maps. Accessed Feb 2022
Goff J, Cain G (2016) Tsunami databases: the problems of acceptance and absence. Geoforum 76:114–117
Goff J, Terry JP (2016) Tsunamigenic landslides—The Pacific Islands blind spot? Landslides 13:1535–1543

Goff J, Chagué-Goff C, Terry JP (2012a) The value of a Pacific-wide tsunami database for risk reduction–putting theory into practice. Geol Soc Spec Publ No 361:209–220

Goff J, McFadgen BG, Chagué-Goff C, Nichol SL (2012b) Palaeotsunamis and their influence on Polynesian settlement. The Holocene 22:1061–1063

Grilli ST, Tappin DR, Carey S et al (2019) Modelling of the tsunami from the December 22, 2018 lateral collapse of Anak Krakatau volcano in the Sunda Straits, Indonesia. Sci Rep 9:11946

Gusman AR, Roger J (2022) Hunga Tonga—Hunga Ha'apai Volcano-Induced Sea Level Oscillations and Tsunami Simulations. GNS Sci Webpage. https://doi.org/10.21420/DYKJ-RK41

GVP (2022a) Report on Hunga Tonga-Hunga Ha'apai (Tonga). Weekly volcanic activity report, 12 Jan–18 Jan 2022, Sennert, S.K. (ed.), Global volcanism program, Smithsonian Institution and US Geological Survey. https://volcano.si.edu/ShowReport.cfm?doi=10.5479/si.GVP.WVAR2022a0112-243040. Accessed Jan 2022

GVP (2022b) Report on Hunga Tonga-Hunga Ha'apai (Tonga), Weekly volcanic activity report, 19 Jan–25 Jan 2022, Sennert, S.K. (ed.), Global volcanism program, Smithsonian Institution and US Geological Survey https://volcano.si.edu/showreport.cfm?doi=GVP.WVAR2022b0119-243040. Accessed Jan 2022

GVP (2022c) Report on Hunga Tonga-Hunga Ha'apai (Tonga), Weekly volcanic activity report, 2 Feb–8 Feb 2022, Sennert, S.K. (ed.), Global volcanism program, Smithsonian Institution and US Geological Survey. https://volcano.si.edu/showreport.cfm?doi=GVP.WVAR2022c0202-243040. Accessed Jan 2022

Harkrider D, Press F (1967) The Krakatoa air—sea waves: an example of pulse propagation in coupled systems. Geophys J Int 13:149–159

Harrison G (2022) Pressure anomalies from the January 2022 Hunga Tonga-Hunga Ha'apai eruption. Weather 77:87–90

Hite EB, Garvin JB, Slayback DA, Burke EA, Callahan G, Joyce P, Whittaker K (2020) Exploring the human-nature dynamics of Hunga Tonga Hunga Ha'apai, Earth's newest landmass. J Volcanol Geoth Res 401:106902

Kataoka R, Winn SD, Touber E (2022) Meteotsunamis in Japan associated with the Tonga Eruption in January 2022. Sci Online Lett Atmos. https://doi.org/10.31223/X55K8V

Keating BH, McGuire WJ (2000) Island edifice failure and associated tsunami hazards. Pure Appl Geophys 157:899–955

Klein A (2022) Tongan volcano erupts. New Sci 253(3370):7

Kusky TM (2022) Déjà vu: might future eruptions of Hunga Tonga-Hunga Ha'apai volcano be a repeat of the devastating eruption of Santorini, Greece (1650 BC)? J Earth Sci 33:229–235

Lamb H (1917) On waves in an elastic plate. Proc R Soc Lond Ser A 93:114–128

Lavigne F, Morin J, Wassmer P, Weller O, Kula, T, Maea AV, Kelfoun K, Mokadem F, Paris R, Malawani MN, Faral A, Benbakkar M, Saulnier-Copard S, Vidal CM, Tu'I'afitu T, Kitekei'aho F, Trautmann M, Gomez C (2021) Bridging legends and science: field evidence of a large tsunami that affected the Kingdom of Tonga in the 15th century. Front Earth Sci 9:748755

Lowe DJ, De Lange WP (2000) Volcano-meteorological tsunamis, the c. AD 200 Taupo eruption (New Zealand) and the possibility of a global tsunami. Holocene 10:401–407

Manneela S, Kumar S (2022) Overview of the Hunga Tonga-Hunga Ha'apai volcanic eruption and tsunami. J Geol Soc India 98:299–304

Marine Industry News (2022) Tonga eruption triggers Peru oil spill. https://marineindustrynews.co.uk/watch-tonga-eruption-triggers-peru-oil-spill/. Accessed Apr 2022

Matsumoto K (2022) Large-scale eruption off the coast of Tonga. Why did an unexpected tsunami occur? News Commentators Bureau, NHK. In Japanese https://www.nhk.or.jp/kaisetsu-blog/100/459802.html. Accessed Jan 2022

NASA (2022a) Tonga Volcanic Eruption & Tsunami 2022a. National Aeronautics and Space Administration. https://appliedsciences.nasa.gov/what-we-do/disasters/disasters-activations/tonga-volcanic-eruption-tsunami-2022a. Accessed April 2022

NASA (2022b) Tonga volcano plume reached the mesosphere. National Aeronautics and Space Administration. https://earthobservatory.nasa.gov/images/149474/tonga-volcano-plume-reached-the-mesosphere. Accessed Apr 2022

NOAA (2022) Hunga Tonga-Hunga Ha'apa Volcano-generated Tsunami, Jan 15, 2022. National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory, NOAA Center for Tsunami Research https://nctr.pmel.noaa.gov/tonga20220115. Accessed Feb 2022

Nomitsu T (1935) A theory of tsunamis and seiches produced by wind and barometric gradient. Memoirs College Sci Kyoto Imperial Univ Series A 18:201–214

Nunn PD (1994) Oceanic Islands. Blackwell, Oxford, p 413

Nunn PD (2009) Vanished Islands and Hidden Continents of the Pacific. University of Hawaii Press, Honolulu

Nunn PD (1998) Pacific Island Landscapes. Chapter 8: Origin, landscape and tectonic development of the islands of Tonga. Institute of Pacific Studies, University of the South Pacific, Suva

Pararas-Carayannis G (2003) Near and far-field effects of tsunamis generated by the paroxysmal eruptions, explosions, caldera collapses and massive slope failures of the Krakatau volcano in Indonesia on August 26–27, 1883. Sci Tsunami Haz 21:191–208

Paris R (2015) Source mechanisms of volcanic tsunamis. Phil Trans R Soc A: Math, Phy Eng Sci 373:20140380

Petricca G (2022) Monitoring the massive Tonga volcanic explosion of 15 January 2022 from Stornoway, Scotland. Weather 77:108–109

Press F, Harkrider D (1966) Air-sea waves from the explosion of Krakatoa. Science 154:1325–1327

Proudman J (1929) The effects on the sea of changes in atmospheric pressure. Geophy Suppl Monthly Notices Royal Astr Soc 2:197–209

Risk Frontiers (2022a) Hunga Tonga-Hunga Ha'apai Eruption 15th of January 2022a. Risk Front Brief Note 458

Risk Frontiers (2022b) Why the Tonga tsunami arrived much earlier and much larger than expected. Risk Front Brief Note 460

RNZ (2022) Tonga eruption likely the world's largest in 30 years–scientist. Radio New Zealand. https://www.rnz.co.nz/news/world/459657/tonga-eruption-likely-the-world-s-largest-in-30-years-scientist. Accessed Jan 2022

Sekizawa S, Kohyama T (2022) Meteotsunami observed in Japan following the Hunga Tonga eruption in 2022 investigated using a one-dimensional shallow-water model. Sci Online Lett Atmos. https://doi.org/10.31223/X5KS78

Smart D (2022) The 1st hour of the paroxysmal phase of the 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption as seen by a geostationary meteorological satellite. Weather 77:81–82

Tanioka Y, Yamanaka Y, Nakagaki T (2022) Characteristics of the deep sea tsunami excited offshore Japan due to the air wave from the 2022 Tonga eruption. Earth Planets Space 74:1–7

Terry JP, Goff J, Winspear N, Bongolan VP (2019) Recognising the perils of landslide-generated tsunamis in the Asia-Pacific region. Nat Hazards 97:1413–1416

Thorarinsson S (1966) The Surtsey eruption: Course of events and the development of Surtsey and other new islands. Surtsey Res Prog Rep 2:117–123

Toulkeridis T, Martinez N, Barrantes G, Rentería W, Barragan-Aroca G, Simón-Baile D, Palacios I, Salazar R, Salcedo-Hurtado EDJ, Pararas-Carayannis G (2022) Impact and response in Central and South America due to the tsunami generated by the submarine eruption of Hunga Tonga-Hunga Ha'apai volcano. J Tsunami Soc Int 41:1–38

Tsunami hazard assessment for Tongatapu, Tonga. Australasian Coasts & Ports 2021 conference, Dec 2021 Christchurch, New Zealand

Vilibić I, Rabinovich AB, Anderson EJ (2021) Special issue on the global perspective on meteotsunami science: editorial. Nat Hazards 106:1087–1104

Williams DA, Horsburgh KJ, Schultz DM, Hughes CW (2021) Proudman resonance with tides, bathymetry and variable atmospheric forcings. Nat Hazards 106:1169–1194

Wilson R (2022) January 15, 2022. Tsunami Advisory in California from Tonga Volcanic Eruption. TsuInfo Alert 24:9–10

World Bank (2022) The January 15, 2022 Hunga Tonga-Hunga Ha'apai eruption and tsunami, Tonga: Global rapid post disaster damage estimation (GRADE) report. International Bank for Reconstruction and Development / The World Bank, Washington DC, p 42

Yuen DA, Scruggs MA, Spera FJ, Zheng Y, Hu H, McNutt SR, Thompson G, Mandli K, Keller BR, Wei SS, Peng Z (2022) Under the surface: Pressure-induced planetary-scale waves, volcanic lightning, and gaseous clouds caused by the submarine eruption of Hunga Tonga-Hunga Ha'apai volcano. Earthquake Res Adv. https://doi.org/10.1016/j.eqrea.2022.100134

ZDNet (2022) Volcanic eruption takes out Tonga cables. https://www.zdnet.com/article/volcanic-eruption-takes-out-tonga-cables. Accessed Mar 2022

Zuo M, Zhou T, Man W, Chen X, Liu J, Liu F, Gao C (2022) Volcanoes and climate: sizing up the impact of the recent Hunga Tonga-Hunga Ha'apai volcanic eruption from a historical perspective. Adv Atmos Sci. https://doi.org/10.1007/s00376-022-2034-1

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.