THE JANUARY 15, 2022
HUNGA TONGA-HUNGA HA'APAI ERUPTION AND TSUNAMI, TONGA

GLOBAL RAPID POST DISASTER DAMAGE ESTIMATION (GRADE) REPORT

Royal New Zealand Air Force P-3K2 Orion reconnaissance flight showing damages in Nomuka Island, Tonga
Photo Credit: New Zealand Defence Force

IN PARTNERSHIP WITH THE GOVERNMENT OF TONGA

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Abbreviations/Acronyms

BRAGSA:	Buildings, Roads and General Services Authority of Saint Vincent and the Grenadines
COPERNICUS EMS:	COPERNICUS Emergency Mapping Service
DaLA:	Damage and Loss Assessment
D-RAS:	Disaster-Resilience Analytics & Solutions, GPURL, World Bank Group
GFDRR:	Global Facility for Disaster Reduction and Recovery
GRADE:	Global RApid post-disaster Damage Estimation
GPURL:	Urban, Disaster Risk Management, Resilience and Land Global Practice
GOES:	Geostationary Operational Environmental Satellite
HOTOSM:	Humanitarian OpenStreetMap Team
HT-HH:	Hunga Tonga–Hunga Ha‘apai
IOM:	International Organization for Migration
JMA:	Japan Meteorological Agency
NEMO	National Emergency Management Office of Tonga
NOAA:	National Oceanic and Atmospheric Administration
OSM:	Open Street Map
PCRAFI:	Pacific Catastrophe Risk Assessment and Financing Initiative program
PDNA:	Post-Disaster Needs Assessment
TEV:	Total Exposure Value
T$:	Tongan Pa‘anga
UNDP:	United Nations Development Programme
USGS:	United States Geological Survey
US$:	United States Dollars
VEI:	Volcanic Explosivity Index

Currency and equivalents: Currency unit = Pa’anga (T$) T$2.30 = US$1.

Contents

Executive Summary

Responding to the Hunga Tonga–Hunga Haʻapai volcanic eruption in Tonga and following a request from the Government of Tonga, the World Bank undertook a rapid post-disaster damage assessment deploying the GRADE methodology.[1] The objective was to estimate the potential direct damage[2] caused by the tephra fall (henceforth referred to as ashfall) and tsunami resulting from the volcanic eruption, to inform the Government's decision-making on financing needs and support development of a roadmap for recovery and reconstruction. There is considerable uncertainty on the detailed impacts of this event since communications with Tonga have been severely disrupted by the damage to the submarine fiber optics telecommunications cable and COVID-19 restrictions that have hampered efforts to carry out ground assessments. This report is valid as of February 7, 2022.

The event has caused economic damage in the order of T$208.0 (US$90.4) million (Table 1) according to this GRADE assessment. However, a resilient recovery which incorporates 'build back better' principles to reconstruct damaged assets to be more resilient will carry immediate and significantly higher costs. There will also be a significant losses component associated with the event due to follow-on disruption in tourism, commercial, agriculture and infrastructure activities associated with the event. These economic losses have not been estimated as part of this GRADE assessment.[3]

1. The volcanic impact was larger than the tsunami impact on agriculture, with around 80% of the damage attributable to the volcanic impact, and 20% due to the tsunami (with some areas affected by both the tsunami and volcanic ashfall). Regarding infrastructure, a combination of tsunami and volcanic ashfall damage was seen in the road, power and water sectors; with the ports and wharfs mostly damaged by the tsunami.
2. A lot of the damage is associated with the tsunami-affected locations for the built infrastructure. The total estimated replacement value of damaged residential buildings is at about half of the estimated damage to non-residential buildings[4], given the significant impact to resorts on islands such as 'Atatā, Fafā and Pangaimotu, as well as on the western coast of Tongatapu. Tourism assets will require significant rebuilding; not only of privately-owned structures and assets, but also public spaces, walkways, moorings, and other associated infrastructure and facilities.
3. While such tourism assets are not the subject of a tourism-specific assessment under this report, they should be given consideration when qualifying impacts on the sector. For example, the extensive damage to the waterfront in Nuku'alofa represents a significant loss to Tonga's tourism attractiveness. A tourism-based recovery strategy including investment needs is recommended given impacts from Cyclone Gita (2018) and Cyclone Harold (2020), as well as this event, in order

[1] Global Rapid post-disaster Damage Estimation (GRADE) approach developed at the World Bank and conducted by the Urban, Disaster Risk Management, Resilience and Land Global Practice (GPURL) Disaster-Resilience Analytics & Solutions (D-RAS) Knowledge Silo Breaker (KSB). The methodology aims to address specific damage information needs in the first weeks after a major disaster. For details of the methodology see here.

[2] Direct damage is quantified using the gross capital stock, which is the replacement cost of an asset rebuilt newly to the same pre-damaged typology and standard. This is not to be confused with book value (depreciated assets)/net capital stock.

[3] Economic damages relate to damage to capital, economic losses refer to loss due to production or business interruption.

[4] Non-residential buildings include tourism related buildings, health facilities, schools, public administrative buildings, religious buildings, commercial offices and private sector buildings

to make all tourism assets and infrastructure resilient to all forms of natural and climate risks. The city's waterfront has been damaged by the tsunami with the waters inundating inland at a distance that has not been experienced during past cyclones and tropical storms. Furthermore, in recent years the city's waterfront has been damaged by cyclones such as 2018 Gita, 2020 Harold and 2021 Yasa. The city's waterfront is therefore now in need of extensive repairs and possibly upgrading to allow for protection from higher surges.

4. Tonga has a number of potential hazards, notwithstanding climate change impacts, and these should be taken into account and assessed in such a strategy to reduce the amount of potential damage from such events and allow the tourism sector to recover more quickly.
5. The impact of this event on the damage side is equivalent to the order of 18.5% of GDP (Table 2).

Table 1: Best estimate of direct damage[2] (values in TOP million).

	Residential Buildings (TOP m)	Non-Residential Buildings (TOP m)	Infrastructure (TOP m)	Agriculture, Forestry, Fishing (TOP m)	Total (TOP m)
Tongatapu	21.3	62.0	33.7	41.4	158.4
Ha'apai	8.7	2.5	3.9	2.5	17.7
'Eua	4.3	1.7	2.6	4.1	12.7
Cable	*0.0*	*0.0*	*7.8*	*0.0*	*7.8*
Subtotal	**34.3**	**66.3**	**48.0**	**48.1**	**196.7**
Ash Cleanup Costs	*11.3*				*11.3*
Total					**208.0**

Table 2: Best estimate of direct damage[2] (values in $US million).

	Residential Buildings ($m)	Non-Residential Buildings ($m)	Infrastructure ($m)	Agriculture, Forestry, Fishing ($m)	Total ($m)
Tongatapu	9.3	27.0	14.7	18.0	68.9
Ha'apai	3.8	1.1	1.7	1.1	7.7
'Eua	1.9	0.8	1.1	1.8	5.5
Cable	*0.0*	*0.0*	*3.4*	*0.0*	*3.4*
Subtotal	**14.9**	**28.8**	**20.9**	**20.9**	**85.5**
Ash Cleanup Costs	*4.9*				*4.9*
Total					**90.4**

Table 3: Best estimate of direct damage[2] (as percentage of GDP based on World Bank staff estimates)

	Direct Damage (as percentage of country GDP)					
	Buildings		Infrastructure	Agriculture	Ash cleanup	Total
	Residential	Non-Residential				
Tonga	3.0%	5.9%	4.3%	4.3%	1.0%	18.5%

"Non-residential Buildings" include tourism-related buildings, health facilities, schools, public administrative buildings, religious buildings, commercial offices and private sector buildings.

"Infrastructure" includes roads, causeways, power supply, ports/marine and water supply networks. Cable represents the damage to the undersea telecommunications cable.

1.0 Introduction

The objective of this report is to provide an estimate of the potential direct damage that has been caused by the tsunami and ashfall that ensued from the January 15, 2022, eruption of the Hunga Tonga–Hunga Ha'apai[5] (HT-HH) volcano in Tonga. This report also provides information on the spatial distribution of current damages, which could support development of a roadmap for recovery and reconstruction. Losses have *not* been estimated as part of this assessment.

The Kingdom of Tonga comprises an archipelago of 169 islands, 36 of which are inhabited. The total surface area of these islands is 729 km^2; 677 km^2 of which are in the inhabited islands. It is noteworthy that Tonga's territorial waters cover 700,000 $km^{2,}$ an area somewhat larger than the surface area of Myanmar (the world's 39th largest country by land area).

HT-HH is one of 22 volcanoes in Tonga. The latest explosive phase of the HT-HH volcano started on December 20, 2021 and reached its paroxysmic phase at 5:15pm (local time) on January 15, 2022. This very strong eruption was described as a once-in-1,000-years event for the Hunga caldera[6], and the event could rank as high as 5 on the zero to 7 volcanic explosivity index (VEI), although more analysis is needed before the volume of erupted material can be estimated more accurately to confirm the VEI. The hitherto joined islands of Hunga Tonga and Hunga Ha'apai covering an area of just over 1 km^2 with a maximum altitude of 149 m, have been blown apart by the eruption, with only very small fragments remaining at the western and eastern edges.

The volcanic eruption set off tsunami waves that seriously affected several inhabited islands in the Tonga archipelago, as well as a Pacific-wide tsunami that reached coasts across the Pacific region and as far as South America, North America, and Northeast Asia much sooner and with higher amplitudes than expected. Around 600 structures in total, including at least 300 residential buildings, have been damaged or destroyed by the tsunami waves in Tonga (around half of these in Tongatapu Island, followed by 'Eua, Fonoifua, Lifuka Mango and Tafisi islands) However, the full extent of the damage has not yet been established (e.g., in Nomuka, Fafā, Tungua, etc.). This matches well with International Organization for Migration (IOM) reports that 1,525 people from 317 households have been displaced in the Tongatapu and Ha'apai island groups. Some moderate impacts have also been reported across different places along Pacific Ocean coastlines.

The eruption plume dispersed ash of 5 to 50 mm thickness across the Ha'apai, Tongatapu and 'Eua island groups. On Tongatapu Island, in which 75% of Tonga's population resides, the thickness of the ashfall was reported to be around 20 to 30 mm. Ashfall thickness reports from other locations around the country

[5] Hunga Tonga–Hunga Haʻapai Island was an uninhabited volcanic island that existed in Tonga from 2015 to 2022, created by undersea eruptions in December 2014 - January 2015 that connect the two separate islands, located about 30 km south of the submarine volcano of Fonuafoʻou, and 65 km north of Tongatapu, Tonga's main island.
[6] Cronin, S. (2022). Why the volcanic eruption in Tonga was so violent, and what to expect next. https://theconversation.com/why-the-volcanic-eruption-in-tonga-was-so-violent-and-what-to-expect-next-175035

have not yet been collated; tephra chemical composition analysis is currently being carried out by the Government of Tonga with support from New Zealand.

2.0 Volcanic Eruption

2.1 Overview of the 2022 HT-HH Eruption as of January 26, 2022

After having been relatively inactive since January 2015, the latest explosive phase of the HT-HH volcano started on December 20, 2021, when a large plume became visible from Nukuʻalofa, Tonga's capital city in Tongatapu Island. Explosions could be heard from at least 170 km away, and the eruption continued until 2:00am on December 21, 2021. Volcanic activity was reduced on January 5, 2022, before restarting on January 13, 2022. The National Emergency Operations Centre was activated on January 14, 2022. This included the outer island Emergency Operations Centers in Ha'apai and Vava'u.

On Friday, January 14, 2022, footage of a strong eruption was captured by the GOES-17 satellite (NOAA) at 4:40am local time, and a tsunami warning was issued for all the islands of the Kingdom of Tonga at 11:12am after swirling abnormal tides drew crowds to the Nuku'alofa waterfront**.** This eruption continued for the rest of the day and into the next day, and probably resulted in the collapse of the caldera (although the exact time when this happened is not yet known), leaving most of the volcano submerged and leading to the separation of the Hunga Tonga island from the Hunga Haʻapai island (as seen on satellite imagery captured the next day on January 15, 2022, at 3:25pm). Later in the afternoon, a Tonga Geological Services (TGS) team observed the eruption from a distance of 2 to 3 miles between 5:00pm and 6:30pm local time, and a nationwide Tsunami warning was issued by the Tonga Meteorological Services. The next day the TGS team reported that observations from satellite images between 5:10pm and 11:30pm (local time) showed that the eruption was continuous, maintaining a 5 km wide column plume of ash, steam and gas rising to altitude 18 to 20 km above sea level. The plume expanded radially up to a radius of 240 km from the volcano, passing over the Tongatapu, 'Eua, Ha'apai and Vava'u island groups. Ashfall has been observed in Tongatapu and other islands. Tsunami waves up to 30 cm were recorded at the tidal gauge in Nuku'alofa.

On Saturday, January 15, 2022, the eruption reached its maximum strength with the explosion that took place at 5:15pm local time and lasted less than 60 minutes. This eruption was captured by the GOES-17 and Himawari-8 (JMA) satellites. The main eruption column rose to a 35 km altitude[7]. Residents of Fiji and Vanuatu (more than 1600 km away) said that ground and buildings were shaking and that sonic 'booms' were also heard, while tsunami evacuations took place in Samoa and Fiji that night. Preliminary data shows that the event was probably the largest volcanic eruption in the 21st century and the largest since the 1991 eruption of Mount Pinatubo. The United States Geological Survey (USGS) reported an earthquake of magnitude 5.8 at 5:15 pm but did not report a moment tensor or focal mechanism solution, indicating that this was not an ordinary earthquake event on an identified fault line.

NASA scientists estimated the power of the blast at between 4 to 18 megatons of TNT equivalent. For comparison, scientists estimate that Mount St. Helens (Washington State, USA) exploded in 1980 with 24 megatons and Krakatoa (Sunda Strait, Indonesia) exploded in 1883, with 200 megatons of energy[8]. **For all**

[7] https://twitter.com/simon_sat/status/1484123252293353475
[8] https://earthobservatory.nasa.gov/images/149367/dramatic-changes-at-hunga-tonga-hunga-haapai

its explosive force, the HT-HH eruption impact was relatively small, compared to the 1991 eruption of Mount Pinatubo (Luzon Island, Philippines), which spewed ash and smoke for several hours, whereas the eruption events at Hunga Tonga-Hunga Ha'apai lasted less than 60 minutes.

The tsunami waves generated by this eruption travelled across the Pacific Ocean, at speeds significantly faster than an earthquake-generated tsunami would have traveled, with on shore wave amplitudes significantly higher than would be expected from an earthquake-generated tsunami. **These basin-wide tsunami waves were generated by the interaction of acoustic gravity waves (caused by the explosion) with water gravity waves (tsunami).** This explains why the tsunami was both larger and arrived much earlier than expected, compared to an earthquake-generated tsunami[9].

A 1.2 m high tsunami wave was observed at Tonga's capital Nuku'alofa on Tongatapu Island, situated about 65 km south of the volcano at around 5:30pm local time, damaging the city's waterfront and some buildings in Sopu and other city neighborhoods. Mass evacuations had taken place across Tonga's coastal areas; this preparedness likely resulted in the low number of human casualties (three lives were reportedly lost to the tsunami waves). Tongatapu Island's west-facing coast in the northwestern peninsula was also badly affected by the tsunami (e.g., in Kanokupolu, Ha'atafu), with higher waves recorded than in Nuku'alofa. Other islands seriously affected by the tsunami were: 'Atatā, Fafā, Fonoifua, Tafisi (Nomuka), Mango, Pangaimotu and Tungua. Less severe damage was seen in islands further away, such as 'Eua and Ha'apai, with the exception of localized areas of the coast such as Ohonua Town, where significant damage was seen. On Ha'apai Island, the foreshore from Pangai to Holopeka was severely damaged, and household damage occurred between Pangai and Houma Tofua. Vava'u and the two Niuas were not affected, but indirect effects such as fuel and other consumer goods shortages are expected.

Telephone and internet lines were cut at 6:40 pm due to damage to the 827 km long submarine fiber optic cable that connects Tonga with Fiji, isolating Tonga's telecommunications to and from the rest of the world. The T$75.4M (US$32.8M) (minus T$10.6M - or US$4.6M savings from TCL) cable had also been damaged in 2019 - from a ship's anchor. The T$25.3M (US$11M) domestic cable will require checks, and there are reports of damage to it close to the volcano[10]. Volcanic ash affected the use of satellite phones, with reports suggesting that only dial-out calls were possible. Because of high costs, the use of satellite phones is limited to government officials and some businesses. It is expected that the repair of the cable will take more than four weeks from the time of the disaster.

The eruption plumes on January 14 and 15, 2022, dispersed ash of 5 to 50 mm thickness across the Ha'apai, Tongatapu and 'Eua island groups, while Vava'u and the Niuas only experienced light ash coverage.

Three of the islands (Nomuka, Mango and Fonoifua) worst affected by the tsunami are in the district of 'Otu Mu'omu'a (Ha'apai group). These three islands had experienced a reduction in population of around 43% between the 2011 and 2021 census. As these islands are more isolated geographically than Tongatapu and reliant on fishing and agriculture for both food and livelihoods, their populations are comparatively more vulnerable to the impacts of the volcano and tsunami. Thus, the value of the capital

[9] https://riskfrontiers.com/insights/why-the-tonga-tsunami-arrived-much-earlier-and-much-larger-than-expected/

[10] *"A preliminary technical fault investigation has established that there are two separate undersea cable breaks. The first between TCL cable landing station in Sopu, Tongatapu and FINTEL cable landing station in Suva, Fiji. The international cable break is approximately 37km offshore from Tonga. The second cable break is on the domestic cable which is near the area of the recent volcanic activity" (Digicel, Jan. 18, 2022).*

stock on these islands is not high in absolute and relative terms. This socio-economic vulnerability would impact potential post-disaster recovery planning. **The people living on the islands of Atatā, Fonoifua, and Mango have been evacuated to Tongatapu,** as damage was very severe, making life on these islands unsustainable until reconstruction has been carried out. The combined population of these three islands as enumerated during the November 2021 census was 211 people. Plans for the re-settlement of these islands are not yet clear, though presumably reconstruction and potentially relocation will need to be considered.

The map on Figure 1 shows the location of Tongatapu and ‘Eua Islands, relative to the HT-HH volcano. The inset shows Tonga’s volcanic arc (17 volcanoes are highlighted) and the latest eruption year for each volcano, as well as the location of Tongatapu and ‘Eua at the southern end of the volcanic arc. The population living on these two islands comprises just over 79% of Tonga’s enumerated population in the November 2021 census.

The HT-HH eruption of December 20, 2021, to January 15, 2022, can be characterized as a Surtseyan eruption type[11]. Surtseyan eruptions are hydro-magmatic, in that they are violently explosive as a result of vigorous interaction between rising magma and lake or sea water. They are characteristically unsteady, with phases of rapid, repeated, short, violent explosions separated by more quiescent phases dominated by steam generation and condensation (as happened in the HT-HH eruption phase between December 21, 2021 and January 15, 2022).

The eruption has also been preliminarily classified as a VEI5 eruption (Cronin, 2022) which suggests that the volume of ejected material would be in the range of 1 to 10 km^3 and the eruption plume would rise 10 to 20 km in altitude. An eruption of this magnitude occurs somewhere on Earth on average once every 12 years.

A key consideration is that the inhabited islands nearest to the HT-HH volcano (’Atatā Island and the Kanokupolu-Ha’atafu peninsula in Tongatapu Island) were situated 55 km away; the Tonga Volcanic Arc is situated well west of the inhabited islands. As aforementioned, in Tonga, for every square kilometer of inhabited land there are more than 1,000 km^2 of sea, and thus the overwhelming majority of the HT-HH volcano ejecta have actually fallen on the ocean waters. The effects this amount of volcanic ejecta may have on fisheries is discussed in the relevant section of this report.

[11] A Surtseyan eruption is an explosive style of volcanic eruption that takes place in shallow seas or lakes when rapidly rising and fragmenting hot magma interacts explosively with water and with water-steam-tephra slurries. The eruption style is named after an eruption off the southern coast of Iceland in 1963 that caused the emergence of a new volcanic island, Surtsey.

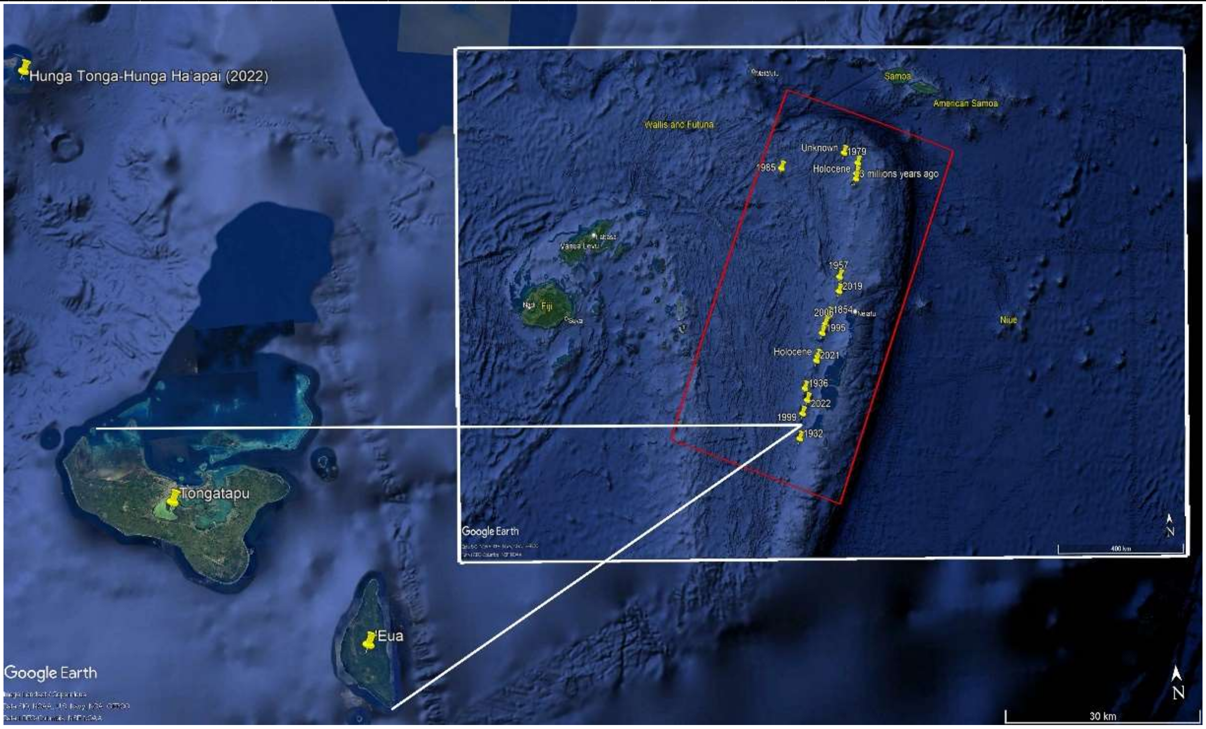

Figure 1: Location of Tongatapu and 'Eua Islands relative to the HT-HH volcano. The inset shows Tonga's volcanic arc (17 volcanoes) and the latest eruption year for each volcano, as well as the location of Tongatapu and 'Eua at the southern end of the volcanic arc.

2.2 Potential Climate Impacts

Detailed observations of the eruption column indicate that the HT-HH eruption ejected a large amount of volcanic material far into the stratosphere up to an altitude of 35 km, leading to speculation that it would cause a temporary climate cooling effect. SO_2 emitted during volcanic eruptions reflects solar radiation back to space and can thus have a cooling impact on the climate system, especially for eruptions in the tropics, where the bulk of the incoming radiation is absorbed. However, later calculations showed that HT-HH injected an estimated 400,000 tonnes of sulfur dioxide gas (SO_2) into the stratosphere, considerably less than in some other major historical volcanic eruptions including Mt. Pinatubo, Philippines (VEI6, 1991) and El Chinchón, Chile (VEI5, 1982) and was unlikely to have any global cooling effect[12]. Despite this, the eruption can have a cooling effect in the Southern Hemisphere[13], causing slight cooling of winters. A cooling effect of 0.1–0.5 °C may last until the next spring in September–November 2022. However, because SO_2 is a toxic, invisible pollutant, for people in Tonga, this could also mean the risk of short-term hazards to human health, including acid rain and 'volcanic smog'.

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[12] https://www.nzherald.co.nz/nz/no-hunga-tonga-eruption-wont-slow-global-warming/MWLPEPNRN4VRRSLRAB6OR6QT7E/

[13] https://www.rnz.co.nz/news/national/459707/tonga-eruption-could-have-cooling-effect-on-southern-hemisphere-scientist

3.0 Direct Damage Estimation for Tonga

The following sectors have been considered for the direct damage estimation: residential buildings, non-residential buildings (including tourism-related buildings, health facilities, schools, public administrative buildings, religious buildings, commercial offices and private sector buildings), infrastructure (including roads, causeways, power supply, and water supply networks), and agricultural crop, livestock and fisheries sector typologies. Note that economic damage estimations provided do not include the impact of economic losses.

This analysis uses capital replacement costs, which is the estimated cost to replace an asset at its pre-damage condition without rebuilding to a different typology or improved building code. This should be differentiated from the reconstruction cost of the asset, in which new building codes and typologies may be implemented at a cost many times that of the original structure. It should also be differentiated from the actual cash value of the property, which is either defined as the book value, or net capital stock, which includes depreciation of the asset. **Generally, replacement costs are more than book value, and less than reconstruction costs**.

Previous volcanic events show that typically, agriculture and infrastructure sectors are often the hardest impacted sectors. Buildings, on the other hand, begin to experience significant damage only when ashfall depths are sufficient to cause roof collapse. General expected levels of damage by ashfall accumulation severity for each sector are summarized in Annex 1. The tables in Annex 1 can be used as a first-order estimation of likely impacts on buildings, infrastructure, and agriculture, for different depths of ashfall.

The 2022 HT-HH volcanic eruption's estimated ashfall accumulation on Tonga was developed using on-the-ground photos and reports, as well as reviewing various ashfall models. This is the DRAS team's modelled estimation based on reported observations, which ranged between 0 and 35mm across the islands, with only some spot reports of higher accumulations (up to 50 mm).

This report does not consider economic losses which are likely to significantly increase the overall economic impact. This could be particularly impactful in sectors such as agriculture and tourism as the loss of associated income due to the damage could be significant.

Damages to infrastructure, agriculture, housing, and livelihoods have a significant impact on the social wellbeing of Tongans, particularly the poor and vulnerable. The Initial Damage Assessment (IDA) team has been deployed to affected areas since January 24, 2022, to verify the extent of the devastation and the needs of the people in the affected areas. Situation reports indicate that approximately 85,000 people have been affected, which is 84% of Tonga's total population. However, entire populations of the islands of Tongatapu, Ha'apai, 'Eua, have been affected by this event.

Reports highlight 600 houses & structures were damaged, and considerable impacts on crops, livestock and fisheries, with 85% of agricultural households (approximately 60,000 people) affected nationwide to some extent. The agriculture sector is an essential sector for the Tongan economy in terms of its contributions to family and household incomes in outer islands and in the greater Tongatapu[14]. In 2015,

[14] Based on World Bank staff assessments and discussion with the Project Management Unit with the Tonga Climate Resilient Transport Project

86% of households were active in agriculture, meeting their own food needs, and most rural households keep livestock (mainly poultry and pigs) for their own consumption. The damage to agriculture and livestock caused by the HT-HH event threatens food security and livelihoods, particularly of the poor and vulnerable, as the incidence of poverty and reliance of agriculture are comparatively higher in rural Tongatapu and in the outer islands.

During the first phase of immediate response, the main humanitarian issues are related to access to safe water, health, shelter, and potential food shortages. A full picture of the impacts on crops, livestock and fisheries is emerging, with comparatively low losses of cassava and yam crops, but high losses of fruit trees and plants (pineapple, banana, mango, pawpaw, soursop) and leafy vegetables (tomatoes, cabbage etc.). Commercial crops (pandanus, sandalwood) showed some form of damage and some loss of livestock (cows, pigs, and ducks).

3.1 Sectoral Damage Estimation from Tsunami and Volcanic Impacts on Tonga

An assessment has been made of the potential cost of damages based on the situation on the ground as reported by local, regional, and international authorities as of January 31, 2022 (Table 1). For this analysis, an ashfall accumulation map was determined by the D-RAS team to best reflect the current accumulations. This analysis was corroborated with analysis by USGS and GNS.

Table 4: Best estimate of direct damage (values in TOP million).

	Residential Buildings (TOP m)	Non-Residential Buildings (TOP m)	Infrastructure (TOP m)	Agriculture, Forestry, Fishing (TOP m)	Total (TOP m)
Tongatapu	21.3	62.0	33.7	41.4	158.4
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Subtotal	**34.3**	**66.3**	**48.0**	**48.1**	**196.7**
Ash Cleanup Costs	*11.3*				*11.3*
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Table 5: Best estimate of direct damage (values in $US million).

	Residential Buildings ($m)	Non-Residential Buildings ($m)	Infrastructure ($m)	Agriculture, Forestry, Fishing ($m)	Total ($m)
Tongatapu	9.3	27.0	14.7	18.0	68.9
Ha'apai	3.8	1.1	1.7	1.1	7.7
'Eua	1.9	0.8	1.1	1.8	5.5
Cable	*0.0*	*0.0*	*3.4*	*0.0*	*3.4*
Subtotal	**14.9**	**28.8**	**20.9**	**20.9**	**85.5**
Ash Cleanup Costs	*4.9*				*4.9*
Total					**90.4**

"Non-residential Buildings" include tourism-related buildings, health facilities, schools, public administrative buildings, religious buildings, commercial offices and private sector buildings.

"Infrastructure" includes roads, causeways, power supply, ports/marine and water supply networks. Cable represents the damage to the undersea telecommunications cable.

Tsunami damage was also estimated using runup data, bespoke modelling and satellite imagery from Copernicus and UNOSAT data, as well as ground reports, in order to establish the extent of inundation for assets, rather than a rapid modelled solution.

3.1.1 Buildings

- The tsunami has caused nearly 100% of the damage to buildings. In most cases, these buildings were swept away with only the foundations remaining along the western coast of Tongatapu, as well as ʼAtatā Island, Nomuka Island, Mango Island, Fonoifua Island, Lifukar Island, and scattered impacts reportedly in Fafā Island and Tungua Island. ʻEua had significant damage along the western coast due to the tsunami with over 100 structures damaged.
- Of T$ 100.5M (US$43.7M) damage to buildings and contents, around two-thirds was to non-residential structures and one-third to residential structures. T$34.3M (US$14.9M) was associated with residential, T$10.1M (US$4.4M) with public and other non-residential buildings, and T$56.1M (US$24.4M) associated with commercial buildings. This is associated with replacement costs (not book value).
- The damage currently seen reflects damage from ashfalls between 15mm and 30mm on Tongatapu, with isolated areas where accumulations of ash have occurred. Even at 50mm, this would be below the threshold where we would expect to see roof collapses in most cases. If there were further **additional ashfall, we may begin to see an increase in the occurrences of roof impacts if roofs are not being cleaned of ashfall, however as of February 7, 2022, photos from Tongatapu show significant efforts have been made towards cleaning roofs, with rainfall events also helping to wash away ashfall**. Due to the salty nature of the ash, it is possible that corrosion may occur in the long-term, and gutters may become clogged. Any solar cells also require cleaning generally for effective energy use. Rainwater harvesting tanks should be disconnected from downpipes while roofs are being cleaned.
- Roof typologies prevalent within housing of groups with lower socio-economic status are more susceptible to roof collapse, generally due to poorer roofing/wall connections to the main structure, and these are generally associated with rural areas, or poorer-quality structures. Metal sheet roofs are used in most buildings especially on Tongatapu (99.5% of buildings according to ADB, 2021). There are a few concrete, tiled, and traditional typologies in addition. Traditional structures generally have thatched roofs.
- There will be significant clean-up costs totaling just under T$11.5 (US$5) million for buildings and paved road infrastructure. Clean-up costs will be in the order of 10% of the total damage seen in the building and infrastructure sectors from both the tsunami and the volcanic effects; however, many times that of the inconsequential direct damage will result from the volcanic ashfall (as very little of the damage was direct volcanic ashfall damage).

3.1.2 Tourism

- Tonga's tourism sector, which represented an estimated 18.5% of GDP in 2019 (prior to international border closures)[15], has been significantly impacted. The industry comprises at least 85 accommodation businesses and 32 land and sea tour operators, with (marketed) accommodation spread across Tongatapu (48 providers), Vava'u (24) Ha'apai (11) and Eua (2), and land/sea tour operators split between Tongatapu (16), Vava'u (14) and Ha'apai (2)
- Most businesses are understood to have been impacted, ranging from incurring volcanic ash deposits, to flooding and structural damage - or complete destruction - by the tsunami. The resort infrastructure on 'Atatā Island, Fafā Island, Pangaimtu and along the west coast of Tongatapu have at least 90 commercial buildings/villas which have been totally destroyed and would require rebuilding, if the owners decide to rebuild. The hotels/resorts also report damages to moorings, boats used for ferrying, and other hotel infrastructure.
- Of the wider tourism related building damage including all destroyed and damaged buildings, around $49.0M (US$21.3M) has been associated with building and contents damage to accommodation facilities and the associated workers homes and buildings (allowing for uncertainty in the building use data from ADB, PCRAFI and OSM). Due to reconstruction after cyclone Harold (where damage (mostly associated with storm surge) was also seen along certain parts of western Tongatapu and further afield), there have been changes to some of the resorts in terms of the number and location of buildings. The reconstructed assets have in some cases now been destroyed. Efforts have been made to ensure that only 2022 stock was included in the assessment, however moving forward, a project to ensure that OSM or local cadasters are up to date after this event could be useful. This can then inform analyses moving forward.
- The tourism sector often exhibits high contents losses, as well as associated costs with rebuilding. The coastline also requires debris removal as part of any replacement of the assets.
- In Nuku'alofa, where the bulk of room supply can be found, several hotels and guesthouses sustained damage from the inundation, but damage has been comparatively low versus the main inundated areas of western Tongatapu and the northern Tongatapu islands. The status of damages to tourism businesses elsewhere, including those in severely impacted locations on Eua and in the Ha'apai group, needs further verification.
- On the losses side, as seen in other events, it can be expected that the swift rebuilding/restoration of reefs, waterfronts, coastal areas, walkways, and other infrastructure will be very important to reduce the follow-on losses.
- The effects of this event are expected to compound a protracted financial crisis that has already challenged Tonga's tourism sector since international borders closed in March 2020. Several businesses that suffered damages and losses following Tropical Cyclone Gita (2018) and Tropical Cyclone Harold (2020) are facing the prospect of a second or third rebuild, if they have the financial means and interest to do so again.
- In terms of public sector tourism assets, according to data collected at the time of the Tropical Cyclone Gita post-disaster assessment in 2018, signage was cited as the only main public sector, tourism-specific 'asset'. However, it is also recognized that public leisure spaces (e.g.,

[15] World Travel & Tourism Council Economic Impact Report Tonga 2019

the waterfront in Nuku'alofa), transport infrastructure (e.g., ports and airports), natural attractions (e.g., reefs), and cultural attractions (e.g., the Palace and tombs) - while primarily serving the local community - are also shared with visitors.

3.1.3 Infrastructure (including Transport, Communications, Power Supply and Water Supply)

- **The infrastructure sector includes capital impacts associated with the water supply and power network, as well as other typologies such as roads. The water supply network and power network are generally affected at lower ashfall depths** with component damage to surfaces, degradation and water infiltration of assets, and replacement of components needed. Around T$48.1M (US$20.9M) in damage has been estimated.
- The tsunami caused damage to water supply tanks, pipes, channels as well as to localized infrastructure for water supply. In addition, ashfall has impacted rooftop tanks (mostly used in rural areas), and wells, with digging out necessary. The freshwater aquifer has been reported safe to drink. Problems of saltwater intrusion and potential ash contamination of this supply may occur in the long term. Chlorination of groundwater is also required in many cases and is being undertaken by the government. Maintenance is also required on the piped stormwater network in Nuku'alofa to clear ash related blockages.
- The power network sustained damage as part of the tsunami as well as through volcanic damage with significant cleaning and repairs required.
- Ports and wharfs have seen differing damage impacts, from no damage to major damage. Along the west coast of Tongatapu, it appears that moorings have been inundated and damaged. At Nuku'alofa Port, New Zealand Defence Force (NZDF) imagery as well as local reports suggest limited to moderate damage, with some surface flooding, contents loss, and some minor damage and components loss, but without catastrophic damage. The port infrastructure in Tongatapu has suffered minor damage but appears to be fully functional with post-disaster humanitarian supplies being successfully unloaded. On 'Eua, significant damage has occurred to the shoreline and surrounding areas in the main township of 'Ohonua. The port building in 'Eua has been completely destroyed while the sea wall and associated concrete structures will require maintenance and repair work.
- Road infrastructure is likely not greatly impacted given the low levels of ashfall; however, some damage to roads and causeways is likely and has been seen on Tongatapu and Pangai Ha'apai (including at the Foa causeway). The key coastal road on 'Eua has extensive damage to the side walls and associated embankment, while significant vegetation loss may contribute to increased sedimentation and potential blockage of the existing culvert.
- The T$64.9M (US$28.2M) submarine cable from Fiji to Tonga sustained significant damage, with exact costs to be determined. Digicel has suggested that damages could be in the order of T$2.3M (US$1M). There is the additional issue of the domestic cable being broken and other cable infrastructure damage and expected delays and difficulties in the cable repair mean that a conservative cost of the infrastructure, works and cable has been pegged at 10% of the cost or approximately T$7.8M (US$3.4M).

- In the Ha'apai group of islands, tsunami damage to the waterfront from Holopeka to Pangai (in Lifuka Island), as well as severe damage to 16 households and government buildings was reported by National Emergency Management Office (NEMO).
- No reports have been received of any damage to transport infrastructure in Vava'u.[16]
- However, on the southern Ha'apai islands, significant damage has occurred to most coastal and inland infrastructure, especially on Tafisi (Nomuka), Mango and Fonoifua islands. Vulnerability functions have been created in accordance with past eruptions for the expected overall power network damage.

3.1.4 Agriculture and Natural Assets

The agriculture sector is, in general, one of the sectors most impacted by volcanic eruptions, and this has proven to be the case in the HT-HH eruption with T$48.1M ($20.9M) damage for the sector estimated due to this event. Damage is very dependent on many factors:

- Grain size, acidity content (pH), chemical makeup and the moisture content of the volcanic ash makes a large difference as to the effects on agriculture.
- Duration length of ash and weather characteristics during this time (rainfall, temperature, wind).
- Growing cycle of the affected agricultural crops, livestock and fisheries.
- Subsistence or export use of crops, where second grade or imperfect products can still be used.

Using the 2015 Agriculture census, the data tables were used to calculate the acreage of each crop type at the village level. This was compared to the market value of crops from consumer price index data in 2021, FAO data from 2020, and previous PDNAs, in order to determine unit costs per acre, yield levels and other sources. The growing cycle has also been considered, as well as preliminary ground assessment information and reports.

- In terms of area, cassava and other root vegetables make up a large percentage of the acres planted and are largely unaffected by the event.
- However, in terms of value, crops such as kava, paper mulberry have generally a higher value associated with the two crops making up a quarter of the agricultural output. Cassava, yam, yautia, sweet potato, forms of taro and other root and tuber crops make up approximately a third of the agricultural output.
- The value associated with long-standing fruit trees also needs to be considered, as often a year of fruit may be lost through volcanic outputs, or the entire tree itself (in the case of tsunami). Banana and plantain trees, as well as citrus (Moli), breadfruit, mango and coconut trees were all affected to some extent in tsunami regions, as well as in other locations across Tongatapu.
- As reported by the government, most root crops showed very little damage (such as yams, sweet potatoes, cassava and taro), and only part of these crops in the late season as well as

[16] FAO (2019) Country Gender Assessment of Agriculture and the Rural Sector in Tonga. https://www.fao.org/3/ca6864en/ca6864en.pdf

in tsunami affected locations will be affected. The long-term impacts are unknown for the soil and productivity, but given the chemical makeup, these are likely to be minimal.

- Leafy vegetables and fruits such as lettuces, tomatoes, pawpaws, mangoes, and pineapples were greatly affected. Cabbage, capsicum, cucumber, and squash were also damaged.
- Cash crops such as vanilla bean plants and kava crops have generally been reported to have survived, but damage to the beans in the case of vanilla has been reported, as well as damage to the plants in certain places regarding kava.
- Handicrafts such as Tapa cloth, are reliant on paper mulberry (Hiapo). Pandanus palm leaves are also used for handicrafts (kiekie, woven mats), and also have fruit. Burnt pandanus leaves are likely a problem in some cases, causing damage to the harvest and plants. Sandalwood has also been affected to some extent.
- Livestock has been largely unaffected with only some scattered reports of deaths due to the tsunami and some isolated reports with ashfall. The effects on livestock can be quick in volcanic eruptions due to fluoride poisoning (in this case the ash did not have a high fluoride content), but also through water and feed contamination. However, the effects can sometimes take several months to show. Modified vulnerability functions have been used to account for the livestock portion.
- Impact on the fisheries sub-sector is one of the major unknowns in this event, given the large amount of damage to reefs as well as the large amounts of ashfall into the oceans. The deep sea fishing industry will largely be unaffected, however damage to shallow reef fishing as well as seafood and aquaculture has been observed. Initial findings from the Ministry of Fisheries confirms significant damages to boats and engines across fishing communities. In addition, the loss of fishing infrastructure such as boats, rods, and other equipment will also likely show larger losses in the sector moving forward.
- This report does not include estimates of direct damage to wildlife and natural assets, although trees are included in terms of the growing cycle costs for 1 year.
- **It should be noted that the agricultural damage is across the whole of Tongatapu**, with the worst affected locations being in western Tongatapu, where ashfall depths are highest and significant tsunami inundation was seen. From an onset of 1mm ash, agricultural impacts can occur (depending on the ash typologies), and above 5mm, significant crop losses can be expected (Annex 1).

3.2 Interpretation of impacts

This section highlights the authors' interpretation of the economic impacts in key sectors. However, we stress the GRADE remote assessment cannot replace an on-the-ground detailed analysis of each building. For single buildings it is not advisable to give a detailed damage value remotely, given intricacies of inundation characteristics, water height or for volcanic eruptions, the depth and chemical makeup of ashfall and grain size as well as detailed characteristics of the impact on the building to be examined. Therefore, the GRADE method adopts a more aggregated approach. When there is a group of buildings, the vulnerability functions are able to average out the errors from any single building, and also give the mixture of building codes, roof types and other typologies; and to give a robust damage estimate.

To further substantiate the results, as part of the GRADE assessment, the team collaborated with several international research and academic institutions to substantiate findings and learn from experts in relation to volcanic ash dispersal and impact of the HT-HH's past and present eruptions in Tonga. These discussions focused on the impact of ash on different sectors such as on housing, health, agriculture, water and sanitation, tourism and transport, and helped to validate our key findings. The GRADE assessment also considered: a) understanding of increased salinity of water due to ash based on geochemical studies; b) spatial distribution of ash and consequent thicknesses of ashfall based on advection-convection ashfall models that impact probabilities of building collapse; and c) collation of damage distribution data and differentiation between tsunami and volcanic damage. The WB team also wishes to acknowledge the support and guidance of ADB and ARUP in relation to the exposure database developed for Tongatapu (Tongatapu Multi Hazard Disaster Risk Assessment 2021, GoT, and ADB). The database provided the foundation for a more detailed understanding of the exposure distribution, land use classification and vulnerability across the island.

3.2.1 Education

Tonga has a total of 179 schools (127 primary, 52 Secondary) across the island groups. While IDA reports are still pending, the United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) has indicated that **a total of six schools—three in Tongatapu and three in Ha'apai—have been damaged along with building contents**. Classrooms, staff-houses, and Early Childhood Education facilities are among the reported damaged assets in need of reconstruction.

3.2.2 Health

Several health considerations are of immediate concern for Tonga, but many may be difficult to monitor without a reliable surveillance system. These include the risk of respiratory illness from ashfall, which may be severe for people with chronic respiratory diseases, e.g., asthma and chronic obstructive pulmonary disease. Good nutrition is also likely to be affected given damages to agriculture and crops and other food sources, e.g., marine and freshwater.

Tonga has 34 health facilities spread across the island groups, with 17 in Tongatapu, one in 'Eua, seven each in Ha'apai and Vava'u, and two in Niuas. **Informal reports indicate that health facility infrastructure damages are minimal in Tongatapu.** Due to its proximity to the HT-HH volcano, the health facilities of the Ha'apai group of islands are particularly vulnerable. The health facilities in Ha'apai are also the most low-lying in comparison to the other island groups[17], with health facilities estimated to be situated anywhere from 3 m (Ha'afeva) to 12 m (Princess Fusipala Hospital) above sea level.

From compound impact perspective related to COVID-19, through tight border controls, Tonga has, to date, made good progress on vaccination[18]. To avoid importation of COVID-19 as part of relief efforts, Tonga has requested contact-less assistance;[19] however, as of February 2, 2022 there are reported cases of COVID-19. The probable impact of COVID-19 community transmission on health service delivery would

[17] Health facilities location estimated height above sea-level: Tongatapu (Range: 4 – 67m), E'ua (94m), Vava'u (Range: 18 -78m), Ha'apai (3 -12m) and Niuas (Range: 11 – 76m)

[18] The country has partially vaccinated 70% and fully vaccinated 60% of the total population

[19] https://www.theguardian.com/world/2022/jan/27/covid-stricken-australian-aid-ship-makes-contactless-delivery-to-virus-free-tonga

likely be compounded by Ministry of Health staff being diverted to disaster response including cleaning and rebuilding efforts, putting additional pressure on an already stretched health care system.

3.2.3 Social Protection

Damages to infrastructure, agriculture, housing, and livelihoods have a significant impact on the social wellbeing of Tongans, particularly the poor and vulnerable.

At least 600 structures were damaged of which at least half were residential and a considerable loss in crops and livestock, with 85% of agricultural households (approximately 60,000 people) affected nationwide to some extent. The agriculture sector is an essential sector for the Tongan economy in terms of its contributions to family and household incomes in outer islands and in the greater Tongatapu.[20] In 2015, 86% of households were active in agriculture, meeting their own food needs. Most rural households keep livestock (mainly poultry and pigs) for their own consumption.[21] The damage to agriculture and livestock caused by HT-HH events threatens food security and livelihoods, particularly of the poor and vulnerable, as the incidence of poverty and reliance of agriculture are comparatively higher in rural Tongatapu and in the outer islands.

During the first phase of immediate response, the main humanitarian issues are related to access to safe water, health, shelter, and potential food shortages.

The Government of Tonga is responding to the above needs with the following measures in the social protection sector:

- The Government has disbursed top-ups of T$ 200 (US$87.0) to beneficiaries of the Elderly and Disability Social Welfare Schemes.
- Every family in affected islands (geographical and actual damage-based targeting) will receive a one-off cash grant in the amount of T$ 500 (US$217.3) for those households that have sustained severe damage to their houses after government inspection. This payment is on top of the top-ups disbursed to the elderly and people living with disabilities.
- Safety and Protection cluster members (Tonga Red Cross, Tonga National Youth Congress, Caritas and Tonga Family Health and Tonga Health Association) installed tents at Kanokupolu and provided food rations, dignity kits, hygiene kits, and tents, as well as counselors for psychosocial support.
- Ongoing psychosocial support provides relief to affected communities through Ministry of Internal Affairs (MIA) offices and through the council of churches (a telephone line).
- IOM is providing advisory and technical support to NEMO in relation to displacement and evacuations.

[20] Based on World Bank staff assessments and discussion with the Project Management Unit with the Tonga Climate Resilient Transport Project.

[21] FAO (2019) Country Gender Assessment of Agriculture and the Rural Sector in Tonga. https://www.fao.org/3/ca6864en/ca6864en.pdf

3.3 Ashfall Clean-up and Disposal Costs

Although the amount of ash that has fallen on the Ha'apai, Tongatapu and 'Eua Island groups was not extreme in comparison to other historic eruptions around the world, the effects on health, buildings, machinery, agriculture, livestock can still be significant. Ashfall is one of the most widely dispersed effects of volcanic hazards; at times affecting communities hundreds of kilometers away, sometimes for many years, due to ongoing eruptions or remobilization of deposits.

Following an eruption, one of the main concerns and challenges beyond the direct damage effects is the provision of access to safe drinking water, as water supplies can be contaminated by the ash, especially for families who rely on rainwater tanks as their main water source. Tongan authorities have responded to this challenge by establishing water stations across Tongatapu and distributing water supplies across all affected communities in the country. Initial damage assessments have also been carried out by the Tongan authorities to assess the impacts of ash and tsunami on agriculture and livestock. However, the potential impact and associated clean-up costs related to the effects of ash on buildings and roads has not yet been fully addressed.

Post-eruption clean-up of ash deposits is a prevalent and expensive (time and resource) activity which is often not planned for adequately. The time and effort required to remove and dispose of ash depends on the depth and aerial extent of the deposits, especially in urban and populated areas, and the availability of machinery to clean it up. Clean-up operations can take from weeks to months to complete. For example, in Tonga, although the Fua'amotu International Airport in Tongatapu was made operational a few days after the eruption due to concerted clean-up efforts of the runway to allow landing of humanitarian relief flights, the airports in Ha'apai and Vava'u remain closed two weeks after the event due to the lack of heavy machinery to clear the runways. Likewise, the port of Nuku'alofa has been cleaned-up within the first two weeks of the eruption, but information on the effects of the tsunami and ashfall on ports in Ha'apai Islands and their post-eruption recovery is still emerging.

Historic review studies from previous eruptions around the world since 1965 suggest that urban areas with small ash accumulations (1,000 m^3/km^2 or an average of 1 mm thickness) may collect <1% of the total deposit, whereas urban areas which experience large accumulations (>50,000 m^3/km^2 or an average of 50 mm thickness) remove up to 80% (Hayes et al., 2015).

Our spatial analysis for Tongatapu Island suggests that on average, the thickness of the ashfall on building roofs would be around 22 mm or around 113,000 m^3 of ash in total, equivalent to 4 m^3 of ash for an average building footprint of 141 m^2, while for the entire island's surface area (260.5 km^2) the total mass of ashfall could have reached as much as 6 million tons. The Tonga Chamber of Commerce and Industries reported that, "businesses surveyed were facing ash clean-up costs of from T$ 110 - 10,560" (US$48 to US$4,646), suggesting that the clean-up costs are going to be sizeable for the private sector.

Our estimate for the clean-up cost of buildings in Tongatapu is T$6.81M (US$2.96M), assuming full clean-up costs for the non-residential buildings (exterior and interior clean-up of building roofs and surrounding yards and pavements) and only pick-up and disposal costs for the residential buildings (assuming that households would self-finance the clean-up of their properties).

For the case of the road network on Tongatapu Island, the total roads length is 1,191 km, of which around 27% is paved, 27.5% is unpaved and 45.5% are informal tracks. Our spatial analysis suggests that on average, the thickness of the ashfall on the road tarmac would be around 20 mm, suggesting a total amount of ash on the road surfaces of around 193,000 m^3, as the average road width is approximately 8.3 meters.

Our estimate for the clean-up cost of the roads in Tongatapu is T$ 4.09M (US$1.78M), assuming full clean-up costs for tarmacs of the paved roads (clean-up of the tarmac, pick-up and disposal) and no clean-up costs for the unpaved roads and the informal tracks.

We can make a comparison with the ash clean-up costs for the Caribbean Sea islands of Saint Vincent and Barbados that were affected by the April 2021, La Soufriére eruption. In Saint Vincent Island (surface area of 345 km^2 and population of around 100,000 at the time of the event) the environmental clean-up/recovery costs were estimated by the government to reach T$32.06M (US$13.94M)[22], of which nearly 75% was for ash cleanup, debris removal, and river cleaning, around 13% for community brigades and road cleaning crews, and around 12% for logistics, trucking of waste and debris and other needs as well as for purchase heavy equipment and vehicles. Ashfall thicknesses on the island ranged from around 1000 mm at the foothills of the volcano to around 10 mm for the more densely inhabited southern part of the island, where the capital city of Kingstown is situated. It is thought that this amount does not cover the full clean-up needs for the evacuated 'red' zone situated on the north of the island (nearest the volcano) where\ashfall thickness in the inhabited settlements was in the order of 50 to 300 mm. It is also not clear if these costs include assets other than building and road assets.

In addition, the UNDP's PDNA estimated that the total damages would reach T$354.4M (US$154.1M) (equivalent to 19% of the GDP). and the losses would reach T$186.3M (US$81M)[23]. The Buildings, Roads and General Services Authority (BRAGSA) estimated a total clean-up cost of the road network of T$13.18M (US$5.73M) (almost 81% of which in the 'red' zone and the rest in the 'orange', 'yellow' and 'green' zones) and an additional T$0.34M (US$0.13M) was required in the airports, especially in the Argyle International Airport.

In Barbados Island (with a surface area of 439 km^2 and population of around 290,000 at the time of the event), located about 190 km east of Saint Vincent, the volcanic crisis response costs were estimated by the government to reach T$100.17M (US$43.55M)[24] (equivalent to 1% of the GDP). Around 25% of this total is related to the ash clean-up operations. The total sum includes beyond the direct clean-up costs and direct damage to crops, livestock, housing, vehicles, equipment, and other assets; the significant losses to economic activity. Around 15% of the total costs were for the wages of hundreds of workers who have been contracted to assist in the ash clean-up campaign and for companies hired to clean the roadways, culverts, drains and wells (over 40,000 sacks of ash have been collected), associated with the Ministry of Transport, Works, and Water Resources. Another 10% was also related to the ash clean-up operations related to the Ministries of Education, Tourism, Industry and International Business, the Prime Minister's Office, the Attorney General and another ten ministries and government agencies. These clean-up costs cover roads, drainage systems, public buildings, public spaces, and then support for individuals and households who were not able to undertake the clean-up themselves.

[22] https://www.stvincenttimes.com/100-2-million-dollars-for-18-of-the-most-pressing-needs/
[23] https://www.bb.undp.org/content/barbados/en/home/library/undp_publications/post-disaster-needs-assessment---st-vincent-and-the-grenadines.html
[24] https://gisbarbados.gov.bb/blog/minister-caddle-87-million-ashfall-impact/

On the residential sector the Sanitation Service Authority sent their trucks out to remove bagged ash from properties based on some simple rules to be followed such as: a) clear separation of household waste and ash waste as the latter could damage the compactor trucks used for household waste (normal garbage collection would not be affected as open-back trucks were being utilized for the pick-up of the ash bags); b) for the ash waste use crocus bags, sugar bags, feed bags – do not use plastic bags and not the normal garbage bags; c) observe the ash waste bag pick-up schedule in your parish, as the collection took place across a six-day period (from April 21 to 28, 2021), with two parishes visited per day.

4.0 Conclusions and Recommendations

The event has caused economic damage in the order of T$207.9M (US$90.4M). However, a resilient recovery which incorporates 'build back better' principles to reconstruct damaged assets to be more resilient will carry immediate and significantly higher costs. There will also be significant economic losses associated with the event due to follow-on disruption in tourism, commercial, agriculture and infrastructure activities associated with the event.

1. The economic damage impact was mostly concentrated in Tongatapu (and the islands around Tongatapu), with Tongatapu accounting for around 76% of the total damage cost.

2. The impact of this event on damages is equivalent to the order of 18.5% of GDP and directly around 2% of capital; however, damage is distributed very unevenly across the islands. With Tonga not experiencing a similar volcanic eruption and related tsunami event in recent history, it is difficult to make comparisons to other historical events, thus the damage distribution cannot be compared directly to past events. However, Tropical Cyclone Harold in April 2020 had economic damages equivalent to greater than T$255.3 (US$111M) (April 23, 2020), and Tropical Cyclone Gita in 2018 had T$208.8M (US$96.2M) in damages (+ T$147.3M or US$67.9M in losses). This event is smaller in terms of economic damages compared to the Cyclone Gita and Harold events; however, for the tourism sector, potentially more damaging. Cyclone Ian in 2014, had damage and losses pegged at T$115M (US$50M) or 11% of GDP.

3. The total estimated replacement value of damaged residential buildings is at about half of the estimated damage to non-residential buildings[25], given the significant impact to resorts on islands such as ʼAtatā, Fafā and Pangaimotu, as well as on the western coast of Tongatapu. These tourism assets will require significant rebuilding of not only structures but also the land, walkways, moorings and other associated infrastructure and facilities.

[25] Non residential buildings include tourism related buildings, health facilities, schools, public administrative buildings, religious buildings, commercial offices and private sector buildings

Table 6: Best estimate of direct damage[2] (values in TOP million).

	Residential Buildings (TOP m)	Non-Residential Buildings (TOP m)	Infrastructure (TOP m)	Agriculture, Forestry, Fishing (TOP m)	Total (TOP m)
Tongatapu	21.3	62.0	33.7	41.4	158.4
Ha'apai	8.7	2.5	3.9	2.5	17.7
'Eua	4.3	1.7	2.6	4.1	12.7
Cable	*0.0*	*0.0*	*7.8*	*0.0*	*7.8*
Subtotal	**34.3**	**66.3**	**48.0**	**48.1**	**196.7**
Ash Cleanup Costs	*11.3*				*11.3*
Total					**208.0**

Table 7: Best estimate of direct damage[2] (values in $US million).

	Residential Buildings ($m)	Non-Residential Buildings ($m)	Infrastructure ($m)	Agriculture, Forestry, Fishing ($m)	Total ($m)
Tongatapu	9.3	27.0	14.7	18.0	68.9
Ha'apai	3.8	1.1	1.7	1.1	7.7
'Eua	1.9	0.8	1.1	1.8	5.5
Cable	*0.0*	*0.0*	*3.4*	*0.0*	*3.4*
Subtotal	**14.9**	**28.8**	**20.9**	**20.9**	**85.5**
Ash Cleanup Costs	*4.9*				*4.9*
Total					**90.4**

Table 8: Best estimate of direct damage[2] (as percentage of GDP based on World Bank staff estimates)

	Direct Damage (as percentage of country GDP)					
	Buildings		Infrastructure	Agriculture	Ash cleanup	Total
	Residential	Non-Residential				
Tonga	3.0%	5.9%	4.3%	4.3%	1.0%	18.5%

"Non-Residential Buildings" include tourism related buildings, health facilities, schools, public administrative buildings, religious buildings, commercial offices and private sector buildings.
"Infrastructure" includes roads, causeways, power supply, and water supply networks.

4. While such tourism assets may not be the subject of a tourism-specific assessment under this report, they should be given consideration when qualifying impacts on the sector. For example, the significant damage to the waterfront in Nuku'alofa represent a significant loss to Tonga's tourism attractiveness. A tourism-based recovery strategy including investment needs is recommended in the face of Cyclone Gita and Cyclone Harold as well as this event in order to make tourism assets and infrastructure resilient to all forms of natural and manmade perils. Tonga has a number of potential hazards, notwithstanding climate change impacts, and these should be taken into account and assessed in such a potential project to reduce the amount of potential damage from such events and allow the resorts to recover more quickly.

5. The volcanic impact was larger than the tsunami impact on agriculture, with around 80% of the damage attributable to the volcanic impact, and 20% due to the tsunami (with some areas affected by both the tsunami and volcanic ashfall). As regards infrastructure, a combination of tsunami and volcanic ashfall damage was seen in the road, power and water sectors, with the ports and wharves mostly damaged by the tsunami waves. Ports and wharves were significantly affected on multiple islands.

6. Agricultural damage, although devastating, was lower than expected due to a different chemical makeup of the volcanic ash deposits, and moderate depths of ash in the order of 15-30mm. The impact on root crops was relatively low, however for fruit and vegetables such as bananas, pineapples, tomatoes and watermelons, the damage was high. Cash crops were also affected, and monitoring is required to see that subsistence farmers and households still have enough produce over the coming months.

7. For the immediate term, recommendations on social protection could include:
    - Continue humanitarian relief and cash payments (such as top-ups provided to the elderly and people living with disabilities).
    - Prioritization of infrastructure services (transport, communications, cleaning of ashes and debris) to support food and water distribution is paramount during this immediate response phase.
    - Look to introduce additional support to households, such as through use of top-ups to poor households which benefit from the Conditional Cash Transfer program under the Skills and Employment for Tongans Program (a measure included in the GoT COVID-19 response in 2021).
    - Consider cash for work to promote immediate employment opportunities for people of all abilities and vulnerable groups in the overall recovery program including reconstruction of houses and clearing off ashes and debris.

5.0 References

Additional references are included in Annex 3: Datasets used.

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Annex 1: Sectoral Impacts and Damage Levels for Different Ashfall Levels

It is seen in previous volcanic events that agriculture and infrastructure are often the hardest impacted sectors, as they begin to experience damage from the onset of only 1mm of ash. Buildings, on the other hand, begin to experience significant damage once ashfall depths are sufficient to cause roof collapse. General expected levels of damage by ashfall accumulation severity are summarized below for infrastructure (Table 1, buildings (Table 2), and agriculture (Table 3). The tables below can be used as a first-order estimation of likely impacts on buildings, infrastructure and agriculture, for different depths of ashfall.

Table 1: Infrastructure. *Approximate median (and interdecile) hazard intensities (using dry ash thickness as a proxy) that relate to key damage and functionality states for a range of critical infrastructure.*

		Code:	D0	D1	D2	D3	D4	D5
		Description:	No damage	Cleaning required		Repair required		Beyond economic repair
CRITICAL INFRASTRUCTURE TYPE:	Airports	Function	Fully functional	Closure of runway				Indefinite closure
		Damage	No damage (but loss of revenue costs)		Possible runway surface degradation	Collapse of critical buildings; possible runway surface degradation [3]		Complete burial
		Thickness	0 mm	>0 mm				>500 mm
	Power	Function	Fully functional	Temporary disruption, e.g. flashover of insulators		Disruption requiring repair		Permanent disruption
		Damage	No damage	No damage to components		Damage to critical components; long delays in receiving replacement components.		Structural damage
		Thickness	0 (0-20) mm	5 (1-20) mm		20 (2-100) mm		>500 mm (100-1000 mm)
	Railways	Function	Fully functional	Reduced visibility and traction	Signals disrupted	Loss of traction making operation unsafe; Possible derailing through ash accumulation		Impassable
		Damage	No damage		Possible abrasion and/or corrosion of signal components and track			Complete burial
		Thickness	0 (0-5) mm	0.5 (0.1-10) mm	1 (0.1-20) mm	30 (2-100) mm		100 (50-200) mm
	Roads	Function	Fully functional	Reduced visibility and traction	Road markings obscured	2WD vehicles obstructed	4WD vehicles obstructed	Impassable
		Damage	No damage		Possible road surface and marking abrasion	Road surface and marking abrasion		Complete burial
		Thickness	0 (0-5) mm	0.5 (0.1-10) mm	2 (1-20) mm	50 (10-100) mm	150 (50-300) mm	n/a [4]

__Table 2: Buildings__. Approximate median (and interdecile) hazard intensities that relate to key damage and functionality states for a range of generic roof types (following Spence et al., 2005 and Jenkins et al., 2014).

Code:		D0	D1	D2	D3	D4	D5
Description:		No damage	Minor/basic repair required	Moderate repair required	Major/specialist repair required		Beyond economic repair
Function:		Functional	Repeated clean-up required; Some loss of functionality for some contents and fittings	Ash infiltration or threat of roof and/or wall collapse may prohibit habitation			Retired
Cost (% of replacement cost):		0 – 1	1 – 5	5 – 20	20 – 60		>60
Structural damage:		No damage	No damage	No damage to principal roofing supports	Partial or complete failure of the supporting structure, e.g. battens or trusses; Partial or moderate damage to the vertical structure		Collapse of roof and supporting structure over 50% of roof area; External walls may be destabilised
Non-structural damage:		No damage	Minor damage to roof coverings, e.g. abrasion and corrosion of metallic roofs.	Potential damage to gutters and roof covering, e.g. excessive bending, and overhangs	Severe damage or partial collapse of roof overhangs; Collapse or partial collapse of roof covering		Partition wall/s destroyed in some cases
Contents and fittings:		Some infiltration of ash possible	Ash infiltration and potential damage to fittings, e.g. air-con, and appliances	Variable levels of contamination and damage			Damage to most contents and fittings is irreversible, or salvage is uneconomical
GENERIC ROOF TYPES:	Timber board on weak timber supports	1 mm?	10 mm?	200 mm (100 – 400 mm) [6]			
	Tiles on timber supports			300 mm (150 – 600 mm) [6]			
	Modest sheeting on timber supports			300 mm (150 – 600 mm) [6]			
	Domestic reinforced concrete			700 mm (400 - 1400 mm) [6]			

***Table3: Agriculture.** Approximate median (and interdecile) hazard intensities (using dry ash thickness as a proxy) that relate to key levels for loss of production for a range of agriculture types. These hazard-loss of productivity relationships are based on expert judgement.*

Code:			D0	D1	D2	D3	D4	D5
Description:			No damage	Disruption to harvest operations and livestock grazing of exposed feed	Minor productivity loss: less than 50 %/crop	Major productivity loss: more than 50 %/crop; Remediation required	Total crop loss; Substantial remediation required	Major rehabilitation required/ Retirement of land[7]
AGRICULTURE TYPE:	Horticulture & Arable	Ground Crops & Arable	0 mm (0-20 mm)	1 mm (0.1-50 mm)	5 mm (1-50 mm)	50 mm (1-100 mm)	100 mm (25-200 mm)	300 mm (100- 500 mm)
		Tree Crops	0 mm (0-20 mm)	1 mm (0.1-50 mm)	5 mm (1-50 mm)	50 mm (1-100 mm)	200 mm (5-500 mm)	300 mm (200- 500 mm)
	Pastoral		0 mm (0-20 mm)	3 mm (0.1-50 mm)	25 mm (1-70 mm)	60 mm (20-150 mm)	100 mm (30-200 mm)	300 mm (100- 500 mm)
	Paddies		0 mm (0-50 mm)	1 mm (0.1-50 mm)	30 mm (1-75 mm)	75 mm (20 - 300 mm)	150 mm (75 – 300 mm)	300 mm (100- 750 mm)
	Forestry		0 mm (0-75 mm)	5 mm (0.1-75 mm)	200 mm (20-300 mm)	1000 mm (100-2000 mm)	1500 mm (100->2000 mm)	?

Annex 2: Methodology & Information Sources

1) Damage extents via photo analysis and social media have been geocoded in order to examine ashfall heights as a first-pass estimate of ash heights allowing for a quick overview of the damaged areas, via the aerial photos, and field survey photos of various individuals, to allow for a first-pass ashfall distribution associated with the aftermath of the 2022 eruption to be created.

2) The various datasets below were integrated together as well as using the data from previous assessments such as censuses, ADB, PCRAFI, OSM and other government datasets in order to create an exposure baseline.

3) Agricultural data has been spatially distributed across Tonga (all 5 islands) using the Land cover patterns as well as growing patterns and the FAO and ministry statistics, especially the 2015 Agricultural census. Vulnerability functions on the basis of previous eruptions in other locations around the globe have been used for the various agricultural crop types, with the associated uncertainty, as well as checks against the geochemical and geotechnical characteristics of the ashfall, and the distribution. Further studies will allow for refinement of these to Tongan settings in future eruptions, however, the functions fit well to first-pass models.

4) The ashfall appears to have not been great enough to cause building damage and collapses (where generally over 15cm is when damage from wet ash starts occurring to buildings) via the vulnerability functions (adapted from GVM, Riskscape, SVG work, CDRPs and previous assessments) which were applied for each of the residential, non-residential and infrastructure components. Very little damage was seen in buildings given the 0-35mm range of ashfall, thus only minor non-structural damage may be present, however for infrastructure and especially agriculture, much damage is seen from the volcanic ashfall).

5) Various checks and isopachs have been examined as part of the previous eruptions from various authors, as well as from previous tsunami events and inundations and these were used with the same vulnerability functions to examine the different levels of potential impact from other potential scenarios.

6) The tsunami was modelled using Tsupy, and applied for a volcanic eruption displacement and shockwave to examine the nearfield and farfield effects and inundation of the tsunami. Over the first couple of days, this was then modified, and finally replaced by on-the-ground satellite assessments of tsunami inundation which were used for the agriculture, building and infrastructure functions in those affected areas.

Annex 3: Datasets Used

Datasets used include:

- Population from Census data in November 2021 and projections
- ADB Tongatapu Project datasets including Land Cover
- Tonga Statistics Agency data on socioeconomic information (including for inflation and capital adjustment)
- Initial Damage Assessments
- Settlement Information
- Tonga PCRAFI data (building attributes, enumeration districts, hotels and other public buildings)
- *Data from the Post Disaster Needs Assessment and Initial Damage Assessments of 2014 CY Ian (Ag/Forestry), 2018 CY Gita - PDNA, 2020 CY Harold – IDA and MoF estimate.*
- Desinventar – Tonga, CATDAT data, historical loss data from other sources.
- Agriculture data from 2015-2019 from Ministry of Agriculture, Forestry, Fisheries with FAO data
- 2015 Agricultural Census

- Infrastructure data from OSM, and ADB
- Building typologies from census data, footprints from OSM and ADB (also through OSM)
- Unit Costs of Construction (UCC) from previous studies and checks against PCRAFI
- GNS, Tonga Government (NEMO and others) and UC reports and discussions
- Social Media reports from Twitter, Facebook including government minister sites
- Capital stock estimates using budget and capital investment data
- Copernicus, Sentinel imagery
- UNOSAT Imagery and Damage grading
- NZDF and ADF disaster response drone imagery
- MORDI Tonga Trust Agricultural data
- ReliefWeb Updates
- World Bank datasets

Annex 4: Volcanism in Tonga

A4.1 Hunga Tonga – Hunga Ha'apai Volcano

Prior to the December 20, 2021 – January 15, 2022 eruption of the HT-HH volcano there were also eruptions in 2014-15, 2009, 1988, 1937, and 1912.

The 2014-15 eruption started on December 19, 2014, and ended on January 23, 2015 (± 3 days), and it was estimated at VEI 2. There were no consequences reported due to this eruption.
The 2009 eruption started on March 16, 2009, when the volcano began spewing steam, smoke, pumice, and ash thousands of feet into the sky. By March 21, lava and ash issuing from two vents—one on the uninhabited island Hunga Haʻapai and another about 100 m offshore were reported. The eruption had filled the gap between the two vents, creating new land surface that measured hundreds of square meters. The eruption devastated Hunga Haʻapai, covering it in black ash and stripping it of vegetation and fauna but it was also the beginning of the process that eventually resulted in the joining of the islands of Hunga Tonga and Hunga Ha'apai (in January 2015) that were eventually blown apart in this year's paroxysmic eruption. The 2009 eruption was estimated at VEI 2.

The initial March 16-17 eruption created an ejecta column which sent ash and smoke up to 20 kilometers into the atmosphere and an initial inspection reported that the volcano had breached the ocean surface. Scientists sailed out to have a closer look at the eruptions of the undersea volcano on March 18 and reported that there was no apparent danger to residents of Nuku'alofa and others living on the main island of Tongatapu. A set of photos from this mission can be seen in this archive article: http://archive.boston.com/bigpicture/2009/03/undersea_eruptions_near_tonga.html and a Moderate Resolution Imaging Spectroradiometer image by NASA's Aqua satellite is seen in this archive article: https://earthobservatory.nasa.gov/images/37572/submarine-eruption-in-the-tonga-islands.

Two Air New Zealand airline flights into Tonga were delayed due to safety concerns caused by the volcanic ash, but flight schedules returned to normal shortly thereafter. Tongan officials also expressed concern that the eruption could significantly harm the country's fishing industry.

Four days after the start of the eruption a strong earthquake measuring 7.6 Mw (USGS) with focal depth at 31 kilometers struck the region. A tsunami warning for islands within 1,000 kilometers of the epicenter was canceled two hours later. Due to its remote epicenter, 191 km south of ‘Ohonua (‘Eua Island), there were no reports of injury or damage from this earthquake in Tonga. However, the ground shaking was fet strongly in Tongatapu Island.

The 1988 eruption occurred from a fissure 1 km south-southeast of Hunga Haʻapai Island; this eruption had a VEI of 0.

The 1912 and 1937 submarine eruptions occurred at a rocky shoal about 3.2 km southeast of Hunga Haʻapai and 3 km south of Hunga Tonga. Both eruption were estimated at VEI 2.

A4.2 Tongan Volcanic Risk

Figure 1 highlights the Tonga Volcanic Arc showing the location, name and year or time occurrence of the last eruption for 17 out of 22 known/named volcanoes in Tonga.

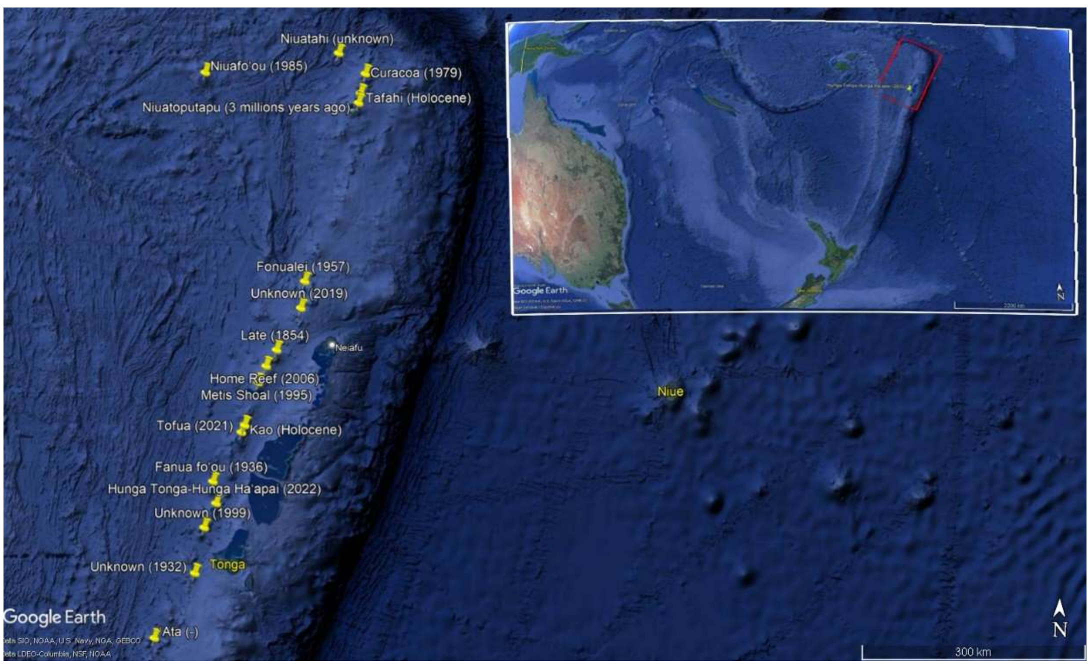

Figure 1: Map of the Tonga Volcanic Arc showing the location, name and year or time of occurrence of the last eruption for 17 out of 22 known/named volcanoes in Tonga. Note that all volcanoes lie west of the inhabited islands, that in turn lie west of the Tonga trench where most of the earthquakes are centered. The inset (red box) shows Tonga’s volcanic arc within the South Pacific region.

Curacoa volcano is a submarine volcano located south of the Curacoa Reef in northern Tonga. The reef is 24fm North of Tafahi in the Niua Islands. Eruptions were observed in 1973 and 1979 from two separate vents. The 1973 eruption produced a large raft of dacitic pumice and had a volcanic explosivity index (VEI) of 3.

Fonuafoʻou volcano, formerly known as Falcon Island, is a submarine volcano in the western part of the Ha'apai group in Tonga. The volcano has created an island several times throughout history. It was first spotted in 1867, while it was still a coral reef. On 11 October 1885, the volcano erupted and sprouted tons of molten lava. Three days later, the eruption created an island, which was named Falcon island by the British. Several eruptions followed in 1894, 1921, 1927, 1928, 1933 and 1936, consolidating the island and expanding its surface (6 km in diameter, 145 meters in height in 1949). In 1949, another eruption caused the explosion and the collapse of the island, which disappeared underwater. New eruptions were recorded in 1970 and 1993. The volcano of Fonuafo'ou is currently −17 meters underwater.

Fonualei volcano is an uninhabited volcanic island in the kingdom of Tonga. It 70km northwest of Vavaʻu and is part of the highly active Kermadec-Tonga subduction zone and its associated volcanic arc. The island is the peak of an active volcano which rises 1000m from the seafloor. It has a diameter of 2km and a maximum height of 188m. In the 1830's the inhabitants of Tokū used Fonualei for their gardens. A major eruption in 1846, starting 11 June, destroyed much of the vegetation of Vavaʻu and spread ash around for at least a year. This is probably a mistake by passing ships who misidentified the erupting island. Another eruption was reported in July 1938.

Home Reef volcano is an ephemeral island built by a submarine volcano whose top has repeatedly broken the surface and afterwards was eroded away by wave action. It is south of Late Island and southwest of Vava'u along the Tofua volcanic arc in Tonga. Home Reef temporarily rose above sea level in island-building eruptions in 1852, 1857, 1984, and 2006. After a volcanic eruption started on 8 August 2006, Home Reef emerged as an island; that eruption also spewed into Tongan waters large amounts of floating pumice, which swept across to Fiji about 350 km to the west of the new island. In October 2006, it reached almost the same size as it did in 1984, when it was about 0.5 km × 1.5 km. The eruptions produced extensive rafts of pumice, which drifted northeast from the new island. The pumice rafts and new island were imaged by NASA's Aqua satellite in August 2006.

Kao volcano is an island and stratovolcano in the Haʻapai island group of Tonga. It lies about 6 km north of Tofua island and reaches 1,030 m above sea level, **the highest point in Tonga**. The date of last eruption is unknown. Although Kao does not display fresh-looking lava flows, it is likely very recent in origin due to the absence of deep gullies or high sea cliffs. The slopes of the island rise at angles exceeding 35 degrees to the summit, which has a series of small volcanic craters. The last reported eruption was on July 10, 1847.

Late Island volcano is an uninhabited volcanic island southwest of Vavaʻu in the kingdom of Tonga. The small, 6-km-wide circular island of Late, lying along the Tofua volcanic arc about 55 km WSW of the island of Vavaʻu, contains a 400-m-wide, 150-m-deep summit crater with an ephemeral lake. The largely submerged basaltic andesite to andesitic volcano rises 1500 m from the sea floor, with its conical summit reaching 540 m above sea level. Only two eruptions have occurred in historical time, both from NE-flank craters, which produced explosive activity and possible lava flows in 1790 and 1854. In August 2019, a large raft of pumice was discovered just northeast of Late Island[26].

Metis Shoal volcano, also known as **Lateiki Island**, is a volcanic island at the top of a submarine volcano in Tonga, located between the islands of Kao and Late. The current island formed in October 2019, when

[26] https://earthobservatory.nasa.gov/images/145490/a-raft-of-rock

a smaller island disappeared after 24 years. In December 1967 an eruption produced another short-lived island, which disappeared by the end of 1968. An eruption in 1979 discharged large amounts of pumice, and formed an island 16km in diameter. The new island was named "Lateiki" and claimed by Tonga in a flag-raising ceremony, but soon eroded beneath the sea surface. During an eruption in 1995, a new island appeared which had a diameter of 280 meters and a height of 43 meters following the growth of a lava dome above the surface. Another eruption happened in October 2019. This eruption was first reported on the morning of 14 October 2019 and continued for more than two weeks. Photos were later taken by aircraft, which showed that Metis Shoal had completely sunk. The Tonga Geological Service announced on 6 November 2019 that the eruption in October produced a new and bigger island, about 120 meters west of the island which disappeared. The new island was estimated to be 100 meters wide and 400 meters long, which is three times bigger than the previous one.

Niuafo'ou volcano is the northernmost island in the kingdom of Tonga. It is a volcanic rim island with an area of 15 km^2 and a population of 431 (as of 2021). The volcano is active and has erupted regularly since 1814, with its last major eruption in 1985. In 1853, an eruption destroyed the village of 'Ahau and killed 25 people. An eruption beginning in August 1886 destroyed buildings and crops and created a new island in the lake. Another in 1912 involved thirty active cones and threw lava to a height of 500 feet. In 1929 an eruption destroyed the village of Futu, cut off the harbor, and killed all the vegetation on the western slopes of the island. In December 1935 an eruption centered on the Ahofakatau and Hina craters caused the evacuation of Belani and Togamamao and produced a two-mile wide lava-flow. An eruption in September 1943 destroyed crops but caused no loss of life. A serious eruption began on 9 September 1946, beginning with a series of tremors and then a lava flow which destroyed the village of Angaha, including the government buildings and the wireless station. The village of Aleleuta was also destroyed and lava flows had left only one third of the island still habitable. The eruption was followed by a series of violent earthquakes. While the inhabitants initially planned to stay, in mid-October the Tongan government issued a compulsory evacuation order. The island was finally evacuated on December 21. The inhabitants were resettled in Nuku'alofa, where land had been provided by Queen Salote. In 1948 they were resettled in 'Eua Island. When they resettled, they named various places in 'Eua after the places they'd known in Niuafo'ou. As a result, the two islands now have many of the same place names. In 1958, about half of the population returned to Niuafo'ou, and the rest remained in 'Eua.

Niuatahi volcano, is a nearly circular submarine caldera in the Tonga Islands. The volcano is 15 km across and rises 1,340 m above the seafloor. The caldera is 9 km wide. The caldera floor lies about 2 km under the ocean, although a 730 m high volcanic cone inside the caldera named Motutahi rises to 1,270 m below sea level. The volcano is surrounded by lava flows extending 60 km from the caldera. Hydrothermal venting takes place adjacent to the inner caldera walls and on the summit of Motutahi.

Niuatoputapu volcano is a high island in the island nation of Tonga, Pacific Ocean. Its highest point is 157 meters, and its area is 16 square kilometers. It is located in the north of the Tonga island group, 300 kilometers away from Vava'u near the border with Samoa. Its closest neighbours are the small island of Tafahi, which is only 9 km to the north-northeast, and the island of Niuafo'ou. Those three islands together form the administrative division of the Niuas. Niuatoputapu Airport accepts international flights. The population was 719 in 2021. It is estimated to have last erupted 3 million years ago.

Tafahi volcano is a small (1.2 km × 2.8 km, 3.42 km^2) island in the north of the Tonga archipelago, closer to Savai'i (Samoa) than to the main islands of Tonga. It is only 9 km north-northeast away from Niuatoputapu, and fishermen commute in small outboard motorboats almost daily between the two. The island has a population of 14 (in 2021). Tafahi is a volcanic island and has the typical cone shape of a stratovolcano rising 560 m above sea level. The soil is extremely suited for growing kava and vanilla, whose exports to the rest of Tonga and beyond is the main occupation of the population. The harbour, only passable by small boats is at the northwest of the island. A steep staircase leads up to the village, with about 69 residents at the census of 2001. There is a primary school on the island. It is estimated to have last erupted in the Holocene era that began approximately 11,650 radiocarbon calibration years before present.

Tofua volcano is a volcanic island located in the Haʻapai island group. It is a steep-sided composite cone with a summit caldera. It is connected to the nearby island of Kao by a submarine ridge. The island is a national park. Its sides rise steeply to the rim of the caldera, which is partially filled by a volcanic crater lake with a depth of 500 m. The caldera was formed by a major eruption around 1,000 years before present, which left deposits up to 0.5 meters thick on islands over 40 kilometers away. The eruptions of 1958–59 caused most of the islanders to evacuate for a year or more. An eruption took place in August 2020-July 2021. No ash advisories were issued during the reporting period; however, intermittent hotspots were detected by Sentinel-2 thermal satellite imagery and Suomi NPP/VIIRS sensor data throughout this period. There was a notable increase in activity during mid-February through July, compared to the previous months, which included distinct sulfur dioxide plumes and consecutive days with thermal anomalies, according to NASA VIIRs satellite data.

Volcano F (also known as Volcano 0403-091) is a submarine volcano in the Tonga Islands. It is located 50 km northwest of Vavaʻu, between Late and Fonualei on the Tofua ridge. The volcano was first mapped in 2004. It consists of a large (8.7 x 6 km) caldera with a depth of 670 - 720 m. The caldera walls are 200 - 300 m high, with the highest peak on the rim only 35 m below sea level. The entire volcano rises 1,000 m from the sea floor. The volcano erupted in September 2001, resulting in an eruption column and a pumice raft which later reached the coast of Australia. In August 2019 a 150 km^2 pumice raft was discovered floating in the Pacific Ocean in Tonga. Discolored water and analysis of the drift path using satellite imagery showed that the raft had originated from an eruption of Volcano F beginning on August 6, 2019.The eruption was preceded by a series of earthquakes on August, 5 and ceased on August 8, 2019.

A4.3 Tsunami hazard from Earthquakes and Volcanoes for Tonga

Tonga is located along the South-Western rim of the Pacific. As island nation along a tectonic plate boundary it is naturally vulnerable to tsunamis triggered either by earthquakes, volcanoes or mass movements. Mass movements and volcanoes are primarily local sources triggered within a few 100s km around Tonga, while earthquakes from all over the Pacific can lead to damaging tsunami run-ups.

Tsunami sources which can affect Tonga can be split into 3 major groups. Distant earthquake tsunamis, local earthquake tsunamis and local volcano tsunamis. Mass movement tsunamis are almost impossible to predict and often linked to either earthquakes or volcanos and here not considered individually.

The historic record of tsunamis affecting is limited, but still reveals frequent impacts. In 1865, 1917, 1919 and 2009 earthquake along the Tonga and Kermadec trench with magnitudes in the range of 8 – 8.5 (Okal et al., 2004) and Okal et al. (2011). There are no records on the actual impact of those earthquakes available from the Tonga islands. However, with run-ups of a few meters on nearby islands, it can be assumed, that the impact on Tonga was not dissimilar. However, distant tsunamis have also affected Tonga in the past. Especially large earthquake along the western coast of South America offshore Peru and Chile can generate very large earthquakes and thus very large tsunamis. The NGDC tsunami database does not provide dedicated run-ups heights for Tonga for those large tsunamis. Only limited data is available on prehistoric tsunami in the region (Goff et al., 2011). However, records from Samoa, French Polynesia, Fiji, New Zealand or Australia can be used an approximation of the wave heights which have been experienced by Tonga. Here, run-ups of 1-4m depending on location, coastal characteristics and initial tsunami size can be anticipated for the potential impact of distant tsunamis.

The historic record on tsunamis is neither complete nor sufficient to quantify tsunami hazards. Even for countries with a long tradition of tsunami protection like Japan, some events may occur unexpected (Geller, 2011). The largest known earthquakes originate at subduction zones where one tectonic plate underrides another and where the release of centuries-long stress accumulation can cause devastating earthquakes and tsunamis. One important aspect of investigating those regions is the approximation of the maximum possible earthquake which is quantified by its magnitude. Both earthquakes of 2004 in the Indian Ocean and the Japan 2011 were beyond the maximum expected magnitude for those subduction zones (Stein and Okal, 2011). For Tonga, 2 subduction zones can be found in the near vicinity, the Tonga and Kermadec trenches. For those subduction zones, literature estimates the maximum magnitudes in the range of 8.4 to 9.4 depending on methodology and previous assumptions (Schaefer and Wenzel, 2019). A full-rupture scenario, with a magnitude 9+, as it was observed in Japan 2011, is in the realm of possibilities, but return periods are uncertain and likely in the range of 1000s of years. However, the last such event, if it even occurred, is currently unknown. This is the situation for many other subduction zones, where the last and largest possible earthquake are not known, e.g. for Central America, the Mariana Trench or the Lesser Antilles Arc. Depending on its exact location, severe shaking would affect all islands in the region and tsunami waves can arrive within minutes. Global tsunami hazard studies (Davies et al. 2018) estimate run-up heights for Tonga on return periods of 500 years of up to 10m and for 2500 years beyond 10m. ADB tsunami assessment (ADB, 2021) tested various earthquake tsunami scenarios under different sea level rise conditions which are likely to increase the overall tsunami hazards in the next decades. Similarly to previous studies like Schaefer et al. (2015), extensive inundation e.g. for Nuku'alofa is possible under worst-case tsunami conditions. In addition to earthquakes, there are several volcanoes, some of them underwater, around Tonga. As it was observed in 2022 for Hunga Tonga-Hunga Ha'apai or for Krakatoa in 2018 and 1883, volcanoes can also trigger tsunamis. Here, a mass movement is observed, e.g. by a caldera collapse, a partial loss of the volcano flank or extensive explosive behavior. For none of these underwater volcanoes, the chance of such an event can be completely ruled out. But usually, the deeper the volcano is underwater, the less likely it is that a mass movement would lead to a tsunami on the water surface.

In conclusion, Tonga was frequently affected (once every few decades) by moderate tsunamis reaching a few meters of run-up either by strong distant earthquakes offshore South America or moderately strong earthquake nearby (M8-8.5). For both cases, the tsunami wave heights can be considered similar or lower than what was experience due to the Hunga Tonga-Hunga Ha'apai tsunami. However, there are also earthquake and volcano sources in the direct vicinity of Tonga where no sophisticated prediction can be made. Various studies indicate the theoretical potential of very strong earthquake along the Tonga trench and several volcanoes have the potential to cause mass movement tsunamis. However, for neither of those it is possible provide discrete probabilities. Thus, uncertainties remain very high. GAR2015 gave an 8 million USD capital damage every 500 years; 44 million USD capital damage for 1000 year RP and 87 million USD for 1500 year RP. There exist a number of historical events on Tonga, and GAR2015 seems to underestimate the relative hazard and risk compared to studies like Schäfer et al., 2015. PCRAFI and others have also created tsunami estimates, however more efforts are needed to create a combined volcano-earthquake tsunami probabilistic loss assessment.

Annex 5: Wider Pacific Regional impact of volcanic eruption

Far-field effects of the Hunga Tonga Hunga Ha'apai (HT-HH) volcano tsunami

The tsunami which had been triggered by the HT-HH volcano was likely bi-modal. The first mode of the tsunami was triggered by a larger underwater mass movement and responsible for most of the destruction in the direct vicinity of the volcano. This first mode was the dominating factor for Tongatapu and its surrounding islands. However, a landslide tsunami like this usually loses the majority of its destructive potential while travelling over the ocean. Thus, the sustaining and partially increasing wave heights on the other end of the Pacific and various water level signals in the Atlantic and Indian Ocean cannot be explained by such a tsunami.

Triggered by the massive volcanic explosion, soon after the eruption, a pressure shockwave was measured all over the globe. Many meteorological stations registered several hPa within a few minutes. A change in air pressure also affects the water surface. An increase in air pressure pushes the water down, while a decrease in pressure lifts it up. 1 hPa change accounts for about 1 cm in water level change. Travelling at the speed of sound (1235 km/h), this shockwave may has triggered the tsunami waves which impacted the other end of the ocean. Since the tsunami was literally pushed by the shockwave and not by a disturbance of sea water at certain place, it was much fast than a usual tsunami. The wave speed of a tsunami which has been triggered somewhere around the Pacific (e.g. by an earthquake) depends on the water depth, usually achieving speeds of about 500-700 km/h in the deep ocean and gets slower in shallow waters. Thus, the initial arrival of the shockwave tsunami was several hours (2-5 h) before the anticipated arrival, which would usually have been the case. In addition, the shockwave tsunami, even though not very high by nature, cased major unrest on the sea surface and constantly increased in strength while travelling over a water body. Thus, the Pacific experienced hours of unrest and the overlap of different wave forms led to the observation that the highest water heights were observed hours after the initial arrival of the shockwave.

With this very unusual tsunami behavior, which was probably observed for the last time about 140 years ago during the 1883 Krakatoa eruption, initial tsunami advisories had to be revised and updated when first observations were clear that the tsunami waves were much stronger than expected. Instead of a few cm of run-up, some places experienced a tsunami with 2m run-up.

Impacts around the Pacific

Both tsunami modes caused damage in several countries around the volcano and the Pacific. For the also significantly affected Lau islands of Fiji, the mass movement tsunami was likely the dominating factor. On several Lau islands, the tsunami damaged houses, roads, and even schools. No casualties have been reported so far.

For almost any other country, the tsunami can probably be linked to the shockwave phenomenon. The most affected regions were harbors located within a bay facing directly into the Pacific (e.g. Santa Cruz, California). Coral reefs and barrier islands (e.g. Los Angeles region) significantly reduced tsunami energy. In addition, the influence of ocean bathymetry on the shock wave tsunami caused some regions to experience on average higher waves than others.

For all affected countries, tsunami advisories were in place which led to evacuation efforts on various coasts. Ports, piers, and beaches were closed. Only for Peru, a national tsunami advisory was not in place when the waves arrived, but it was revised later. Due to the on-going unrest in the sea, several ports have been closed. Damage was mostly observed in small ports and bays. In Santa Cruz, the tsunami flooded a nearby parking lot, damaging neighboring structures and parked cars. In many places, boats were washed away, capsized or damaged, which also lead to damage to port infrastructure like moorings and piers.

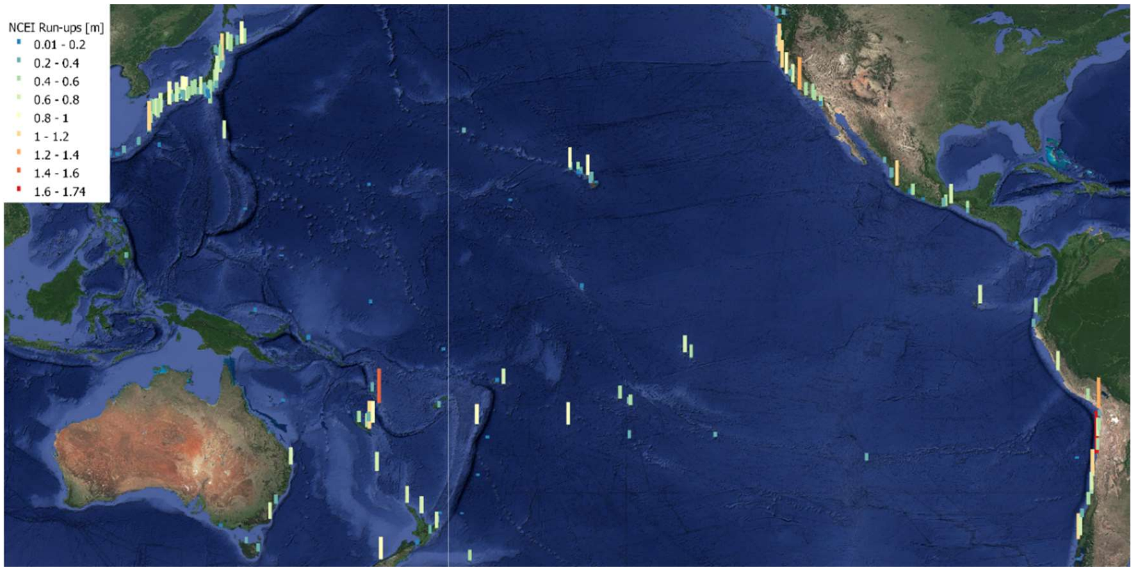

Figure 2: Observed run-up by NCEI water level stations for the Pacific.

Table 4: Far field effects of the HHTH eruption and the tsunami

Location	Latitude	Longitude	Impact
United States			
California			Piers and Beaches were closed Damage to several piers
Santa Cruz	36.955	-122.01	$6 mn. Damage, coupled with high tide Flooding of parking lots (floating cars) and near-coast homes Damage to harbour infrastructure and boats moored there Tsunami waves affected Santa Cruz for about 24h
Crescent City	41.75	-124.2	<< $20 mn. Damage (Tohoku Comparison)
Berkeley	37.86	-112.31	100 ppl. Evacuated from Marina
Santa Barbara	34.41	-119.7	overturned Harbor Petrol boat
Ventura	34.27	-119.28	Several boats swepped away Harbor Patrol boat damaged Boats crashed into each other and also damaged port infrastructure
San Francisco	37.75	-122.51	Surfers, who ignored tsunami advisory, had to be rescued by SFFD.
San Mateo County	37.44	-122.44	2 anglers, who ignored tsunami advisory, had to be rescuved by first responders
Pillar Point Harbor	37.5	-122.48	2 people with lifejackets swept off a jetty, but were able to get back
Marina Del Rey	33.97	-118.45	Minor damage to docks,
Richardson Bay	37.88	-122.49	Minor damage to docks and vessels
Peru			80 ports closed
			nation-wide tsunami advisory was released 1h after 2 people died
Lambayeque	-6.77	-79.97	2 people drowned
La Pampilla	-17.14	-71.87	Oil spill offshore La Pampilla refinery. potential fine of $33 mio.
Paracas	-13.83	-76.25	Damage to a market, loss of stands and and merchandise, inundation along El Chaco coast
			run-up of about 50m
			Restaurants and boats damaged
Ancon	-11.77	-77.18	inundation of coastal infrastructure (piers)
Japan			27 domestic flights were cancelled
Muroto	33.28	134.17	Damage to several boats, some boats sunk
			22 boats sunk, floated away or capsized
Owase	34.07	136.22	A boat sunk
Amami-Oshima Island	28.27	129.39	Coastal Flooding
Kagoshima	31.04	130.72	1 injury
			5 boats capsized

Okinawa	26.31	127.84	1 injury
New Zealand			
Tutukaka	-35.62	174.54	Damage to several boats, some boats sunk
Chile			
Iquique	-20.24	-70.15	Coastal Flooding
Fiji			
Lau Islands	-19.15	-178.52	Several homes damaged and debris left by tsunami
			Some damage and coastal flooding
			Substantial damage to schools, infrastructure and fishing boats

KO E 'OTUA MO TONGA KO HOKU TOFI'A

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