Estimating the eruption-induced water displacement source of the 15 January 2022 Tonga volcanic tsunami from tsunami spectra and numerical modelling

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ABSTRACT

The 15 January 2022 Tonga volcanic tsunami was a unique event as it was the only event after the 1883 Krakatau volcanic tsunami that created waves by a dual-mechanism generation process comprising atmospheric pressure waves and eruption-induced water displacements. Here, we study 22 tide gauge waveforms, eight DART (Deep-ocean Assessment and Reporting of Tsunamis) records, eight air pressure time series, apply spectral analysis, and conduct numerical modelling to develop a source model. Our source model accounts only for the contribution of eruption-induced water displacement. The maximum overall coastal tide gauge amplitudes were in the range of 4.2–148.8 cm, whereas DARTs registered maximum amplitudes of 3.6–21.4 cm. We identified the dominant tsunami periods due to the localized water displacement mechanism as 10–17 min and 4–7 min. The waves generated by atmospheric pressure waves had a period of 7–10 min and an amplitude of 9–19 cm on coastal tide gauges; the corresponding values for DARTs were 30–60 min and 4.2–15.7 cm. Modelling showed that the eruption-induced water displacement source had a characteristic initial length of 12 km, a maximum initial amplitude of 90 m, and a volume of $6.60 \times 10^9$ m$^3$.

1. Introduction

A large and unique tsunami with global reach was generated on 15 January 2022 in the Tonga region due to the volcanic activities at the Hunga Tonga–Hunga Haʻapai (HTHH) volcano (175.382°W, 20.536°S), which is an uninhabited volcanic island in the southwest Pacific Ocean (Figs. 1–2). The event left a death toll of five people and caused approximately US$90.4 millions of damage (Fig. 2) according to the World Bank.1 The resulting tsunami was unique in that the water waves were generated by both the sudden water mass movements due to eruption, and the atmospheric pressure waves caused by the volcanic explosive eruption. Many distant coastlines, for example in the Indian Ocean and the Mediterranean Sea, registered tsunami waves, whose relatively early arrivals can be explained only by taking into account the generation of tsunami by the atmospheric pressure wave, which propagates at high speeds of 312 m/s (Harkrider and Press, 1967) or speed of sound (343 m/s), faster than the moderate speed of long oceanic water waves (100 m/s – 220 m/s at a water depth of 1000 m–5000 m). Therefore, the global tsunami records of the January 2022 Tonga tsunami, generated by the HTHH volcanic eruption, cannot be solely attributed to the oceanic gravity waves propagating through all-water routes from the HTHH volcano, rather they are mixed with those excited by atmospheric pressure waves. A similar situation of tsunami generation by both a localized source and atmospheric pressure waves was previously reported following the giant 1883 Krakatau volcanic eruption and tsunami (Harkrider and Press, 1967; Pelinovsky et al.,
As part of the 15 January 2022 Tonga tsunami, was generated by atmospheric pressure waves, it can be called a meteotsunami as well. The Hunga Tonga–Hunga Ha'apai volcano is located approximately 70 km northwest of Nuku'alofa, which is the capital city of Tonga. The volcano is the result of the ongoing subduction process of the Tonga-Kermadec trench, where the Pacific Plate subducts beneath the Australian Plate (Fig. 1) (Colombier et al., 2018; Bohnenstiehl et al., 2013). Previous records of significant eruptions of this volcano in the 20th and 21st centuries occurred in 1912, 1937, 1988 and 2009 (Bohnenstiehl et al., 2013). During the 2009 volcanic eruption event, violent eruptions generated ash and steam that reached as high as approximately 7 km in altitude and posed risks to air traffic in the region. Possibly the January 2022 event was the largest recorded eruption in the Hunga Tonga–Hunga Ha'apai volcano. Analysis of seismic tremors of the volcanic eruption reveals that the origin time of the largest tsunamigenic eruption was approximately 04:15 UTC on 15 January 2022 (Fig. 3). For this calculation, we considered the distances between the volcano and the seismic stations as well as a speed of 4–6 km/s for the propagation of seismic P waves.

The purpose of this research is to investigate the tsunami waveforms recorded in the near field (distances up to approximately 1,500 km), to characterize the spectral content of the tsunami waveforms and to apply this information for developing a source model for the tsunamigenic source of the event. This study is based on the sea level data from coastal tide gauges, and the Deep-Ocean Assessment and Reporting of Tsunamis (DARTs) (Fig. 1) as well as barometric (air) pressure data. As the recorded tsunami waveforms of the January 2022 Tonga tsunami were generated by two different mechanisms comprising eruption-induced water mass displacement and continuous excitation of oceanic waves from the atmospheric pressure waves, we made efforts to characterize these two types of water waves by analyzing both sea level and air pressure data. For reconstructing the tsunami source, we considered the waveforms from the eruption-induced water mass displacement source; therefore, the source model that we propose in this study does not account for the contribution of atmospheric pressure waves to the observed tsunami.

2 https://earthobservatory.nasa.gov/images/149474/tonga-volcano-plume-reached-the-mesosphere.
Fig. 2. Tsunami inundation and damage as registered by two video recordings of the 15 January 2022 Tonga tsunami along the coast of Nuku’alofa, Tonga. The original videos are from https://www.youtube.com/watch?v=uWiNNJKXE8A (a) and https://www.youtube.com/watch?v=VsHTDXL3XcY (b). Both locations are in Nuku’alofa, which is the capital city of Tonga.

Fig. 3. Seismic records of the 15 January 2022 Tonga eruption on regional seismic stations. Arrival times of the P-phases are marked by black thick lines. The locations of the seismic stations are shown by brown circles in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
coastal areas and thus tsunamis must propagate through various and wide continental shelves (100 m bathymetric features, such as many islands, seamounts, shallow-depth and wide continental shelves (100 m–300 m water depth), ports and harbors, before being recorded on tide gauges. In addition, tide gauges are usually located within harbors, ports and bays and thus are subject to various wave oscillations within these semi-confined water bodies. Therefore, tide-gauge records of tsunamis contain a large mix of waves from the tsunami source, reflected and diffracted waves from islands and seamounts, oscillations due to shelf edge waves and sea-level fluctuations within harbors. On the other hand, DARTs are installed in the deep ocean (water depth of 1,000 m–5,000 m) and therefore many shelf and coastal oscillations are absent from their records, although DARTs may record some reflected or diffracted waves due to islands and seamounts (Satake, 2014; Rabinovich and Eblé, 2015; Rabinovich et al., 2019; Heidarzadeh et al., 2018; Mulia et al., 2022).

Our sea level data comprises 22 tide gauge waveforms and eight DART records (Fig. 1, Table 1). The tide gauge data are provided by the sea level station monitoring facility of the UN Intergovernmental Oceanographic Commission (UN/IOC) available at www.ioc-sealevelmonitoring.org. Three DART data (D-51425, D-52406 and D-55023) belong to the US National Oceanic and Atmospheric Administration (NOAA) (https://nctr.pmel.noaa.gov/Dart/) while five DART records (NZ-G, NZF, NZ-K, NZ-E and NZ-D) are obtained from the New Zealand GeoNet services (https://www.geonet.org.nz/tsunami/dart). The tide gauge and NOAA-DART data are sampled with 1 min intervals, whereas NZ-DART data have sampling intervals of 15 s. Quality control was performed on all sea level data in order to remove gaps, and spikes and to ensure that all data points are equally distributed in time. We calculated the tidal signal using the TIDALFIT package (Grinsted, 2008); the calculated tides were consequently removed from the original records (e.g., Heidarzadeh et al., 2020a,b).

Table 1

| Type       | Station name | Longitude (°E) | Latitude (°N) | Arrival time (min) | Arrival time of eruption-induced water displacement waves (min) | Maximum amplitude (cm) | Theoretical arrival time of air pressure wave (min) |
|------------|--------------|----------------|---------------|--------------------|---------------------------------------------------------------|------------------------|-----------------------------------------------|
| DART       | NZ-G         | -173.401       | -23.352       | 25                 | 45                                                            | 21.4                   | 19.4                                          |
|            | NZ-F         | -175.013       | -29.684       | 56                 | 80                                                            | 11.2                   | 52.4                                          |
|            | NZ-K         | 169.499        | -24.309       | 160                |                                                               | 14.9                   | 82.4                                          |
|            | D-51425      | -176.262       | 9.505         | 130                |                                                               | 8.9                    | 62.9                                          |
|            | NZ-E         | -177.708       | -36.049       | 96                 | 130                                                           | 7.9                    | 89.4                                          |
|            | NZ-D         | 178.604        | -36.099       | N/A                | 145                                                           | 9.6                    | 93.8                                          |
|            | D-52406      | 164.990        | -5.373        | 152                | 255                                                           | 5.0                    | 138.6                                         |
|            | D-55023      | 153.537        | -14.715       | 306                |                                                               | 3.6                    | 171.7                                         |
| Tide       | Suva Viti    | 178.424        | 18.134        | 65                 | 90                                                            | 33.1                   | 35.9                                          |
| gauge      | Mata Utu     | -176.101       | -13.170       | 74                 | 90                                                            | 4.2                    | 42.0                                          |
|            | Apia Upolu   | -171.761       | -13.827       | 75                 | 75                                                            | 24.1                   | 42.9                                          |
|            | Chatham Is.  | -176.369       | -44.025       | 232                | 232                                                           | 76.7                   | 134.2                                         |
|            | East Cape    | 178.159        | -37.550       | 230                | 230                                                           | 93.6                   | 102.3                                         |
|            | Fongafale    | 179.195        | -8.903        | 110                | 150                                                           | 12.2                   | 74.6                                          |
|            | Great Barrier| 175.489        | -36.189       | 180                | 220                                                           | 148.8                  | 100.3                                         |
|            | Huahine Is.  | -151.032       | -16.722       | 220                | 220                                                           | 59.3                   | 133.3                                         |
|            | Lautoka      | 177.438        | -17.605       | 125                | 125                                                           | 17.4                   | 42.0                                          |
|            | Lifou         | 167.279        | -20.918       | 120                | 180                                                           | 73.3                   | 92.3                                          |
|            | Nauru         | 166.909        | -0.532        | 300                | 300                                                           | 15.5                   | 150.6                                         |
|            | Norfolk Is.  | 167.954        | -29.059       | 196                | 200                                                           | 128.0                  | 98.8                                          |
|            | North Cape   | 173.050        | -34.410       | 215                | 215                                                           | 61.8                   | 98.3                                          |
|            | Nuku alofa   | -175.181       | -21.137       | 13                 | 13                                                            | 123.0                  | 3.8                                           |
|            | Quinoo       | 166.683        | -21.983       | 120                | 200                                                           | 116.1                  | 95.5                                          |
|            | Ouvea        | 166.562        | -20.549       | 140                | 200                                                           | 45.8                   | 96.2                                          |
|            | Pago Pago    | -170.691       | -14.277       | 75                 | 75                                                            | 56.3                   | 43.7                                          |
|            | Port Vila    | 168.308        | -17.755       | 180                | 180                                                           | 117.2                  | 89.1                                          |
|            | Barotonga    | -159.783       | -21.2         | 135                | 135                                                           | 55.0                   | 83.2                                          |
|            | Taaranga     | 176.181        | -37.641       | 195                |                                                               | 28.4                   | 106.2                                         |
|            | Thio         | 166.242        | -21.614       | 178                | 200                                                           | 77.5                   | 97.8                                          |
|            | Tubuai       | -149.476       | -23.342       | 225                | 225                                                           | 45.6                   | 137.6                                         |

* Zero-to-crest amplitude.

Table 2

| Station name | Longitude (°E) | Latitude (°N) | Sampling time interval (min) |
|--------------|----------------|---------------|------------------------------|
| Lomaiavana   | 178.42         | -17.960       | 10                           |
| Nadi         | 177.44         | -17.755       | 10                           |
| Auckland     | 174.714        | -36.748       | 10                           |
| Gisborne     | 177.922        | -38.627       | 10                           |
| Ruakura      | 175.305        | -37.774       | 10                           |
| Kaitaia      | 173.287        | -35.068       | 10                           |
| Noumea       | 166.453        | -22.276       | 1                            |
| French       | -149.614       | -17.555       | 1                            |

2. Data and methods

2.1. Sea level data

Data from two types of sea level measurement systems are used in this study: coastal tide gauges and Deep-Ocean Assessment and Reporting of Tsunamis (DARTs) (Table 1). The main difference between them is that tide gauges are located within the ports and harbors in coastal areas and thus tsunamis must propagate through various bathymetric features, such as many islands, seamounts, shallow-depth and wide continental shelves (100 m–300 m water depth), ports and harbors, before being recorded on tide gauges. In addition, tide gauges are usually located within harbors, ports and bays and thus are subject to various wave oscillations within these semi-confined water bodies. Therefore, tide-gauge records of tsunamis contain a large mix of waves from the tsunami source, reflected and diffracted waves from islands and seamounts, oscillations due to shelf edge waves and sea-level fluctuations within harbors. On the other hand, DARTs are installed in the deep ocean (water depth of 1,000 m–5,000 m) and therefore many shelf and coastal oscillations are absent from their records, although DARTs may record some reflected or diffracted waves due to islands and seamounts (Satake, 2014; Rabinovich and Eblé, 2015; Rabinovich et al., 2019; Heidarzadeh et al., 2018; Mulia et al., 2022).
2.2. Atmospheric pressure data

Time series of atmospheric pressure changes at eight stations (Table 2; Fig. 1) across the southern Pacific Ocean are used to study the propagation of the atmospheric pressure waves generated by the Hunga Tonga–Hunga Ha’apai volcano on 15 January 2022. Except for two stations of Noumea and French Polynesia, whose pressure data come with 1-min time intervals, other atmospheric pressure data possess time intervals of 10 min (Table 2). The atmospheric pressure data are provided by the Fiji Meteorological Service (https://www.met.gov.fj/), the National Institute of Water and Atmospheric Research of New Zealand (https://niwa.co.nz/) and Météo France - Direction Interregionale de la Nouvelle Caledonie et de Wallis et Futuna.

2.3. Spectral analysis (Fourier and Wavelet)

To provide a comprehensive insight into the tsunami spectra and the time evolution of dominant tsunami periods, we performed Fourier Transform and Wavelet analyses. While Fourier Transform offers a static account of dominant tsunami periods, Wavelet analysis presents the temporal distribution of those dominant periods. The Fourier Transform in this study is conducted using the Welch (1967) algorithm of Mathworks (2022) by considering Hanning windows and 50% overlaps (e.g., Rabinovich, 1997; Rabinovich et al., 2017; Heidarzadeh and Satake, 2014, 2015a; Heidarzadeh et al., 2019). A 300-min window for both tsunami and background signals were considered. Background signals refer to the part of the waveforms before the arrival of a tsunami at a sea level station. Due to unavailability of background data for DART records with 1-min sampling intervals, we were unable to calculate background spectra for DARTs. The Wavelet package of Torrence and Compo (1998) was used for Wavelet analysis. It has been shown by multiple authors that Wavelet analysis provides significant insights into tsunami research through revealing the temporal evolution of dominant tsunami periods (e.g., Zaytsev et al., 2021; Rabinovich et al., 2021; Heidarzadeh and Mulia, 2021; Heidarzadeh et al., 2015b; Rabinovich and Eble, 2015; Allgeyer et al., 2013).

2.4. Tsunami simulations and tsunami source model

For tsunami simulations, the bathymetric grids provided by the General Bathymetric Chart of the Ocean (GEBCO) (Weatherall et al., 2015; IOC et al., 2003) are used in this study, which offers grids with a spatial resolution of 15 arc-sec. We resampled the GEBCO bathymetric data into a two-level nested grid system with grid sizes of 3 arc-min (for the entire domain in Fig. 1) and 0.75 arc-min (for areas around the source region within longitude 184°–185°W and latitude 20–21°S). The numerical modelling package COMCOT (Cornell Multi-grid Coupled Tsunami Model) was used for tsunami modelling which is based on
solving linear and nonlinear Shallow Water Equations in spherical and Cartesian domains (Wang and Liu, 2006). We applied linear simulations of the Shallow Water Equations on a spherical domain in this study. The time step of the simulations was adjusted based on the Courant number criterion (Courant et al., 1928) to satisfy the stability condition of the numerical stepping scheme. The simulations were conducted for a total time of 10.0 h after the eruption time. The tsunami travel time (TTT) software of Geoware (2011) was used to carry out tsunami travel time analysis. The TTT package applies the Huygen’s principle to calculate tsunami travel times, which assumes that all grid points on a wavefront are considered as point sources for secondary waves (IOC, 2009). It is noted that the TTT programs calculates travel times for the tsunami generated by eruption-induced water displacements at the HTHH volcano and is unable to account for the tsunami due to atmospheric pressure waves. For estimating the travel times of the atmospheric pressure waves, we assumed the propagation of a concentric atmospheric pressure pulse over a sphere with a constant speed of 325 m/s, which was determined from the observed arrival times of atmospheric pressure waves at observation stations in the region (Fig. 1).

To examine the quality of fit between observed and simulated tsunami, we applied the two equations $K$ and $\kappa$ of Aida (1977) which are defined as follows:

$$\log K = \frac{1}{N} \sum_{i=1}^{N} \log \frac{O_i}{S_i}$$

(1)

$$\log \kappa = \sqrt{\left[\frac{1}{N} \sum_{i=1}^{N} \left(\log \frac{O_i}{S_i}\right)^2\right] - (\log K)^2}$$

(2)

where $N$ is the number of stations, $O_i$ and $S_i$ are the observed and simulated peak amplitudes at station $i$, respectively. For a perfect match between observations and simulations, $K$ and $\kappa$ are one and zero, respectively. For $K$ less than 1, simulations overestimate the observations and vice versa. The model can be considered as sufficiently accurate when $0.8 < K < 1.4$ and $\kappa < 1.4$.

3. Tsunami and air pressure waveforms

The de-tided sea level records of the 2022 Tonga tsunami are presented in Figs. 4–7 along with air pressure oscillations at some of the nearby atmospheric stations to the tide gauges. The distribution of maximum tsunami zero-to-crest amplitudes at station $i$, respectively. For a perfect match between observations and simulations, $K$ and $\kappa$ are one and zero, respectively. For $K$ less than 1, simulations overestimate the observations and vice versa. The model can be considered as sufficiently accurate when $0.8 < K < 1.4$ and $\kappa < 1.4$.

3. Tsunami and air pressure waveforms

The de-tided sea level records of the 2022 Tonga tsunami are presented in Figs. 4–7 along with air pressure oscillations at some of the nearby atmospheric stations to the tide gauges. The distribution of maximum tsunami zero-to-crest amplitudes is illustrated in Fig. 8. As the sea level records of the tsunami are a mix of waves generated by the atmospheric pressure waves and those generated by eruption-induced
water displacement (through all-water routes), in order to distinguish the two, we marked the arrival times of waves generated by eruption-induced water displacement, as well as theoretical arrival times of atmospheric pressure waves (Fig. 1; solid red contours) in Figs. 4–7 by green and pink arrows, respectively. The arrival times of the tsunami from the eruption-induced water displacement source are based on the TTT analyses, which are shown by dashed lines in Fig. 1.

4. Characteristics of tsunami waves generated by localized eruption-induced water displacement

Among the 22 tide gauges examined in this study, the maximum tsunami amplitude ranged from 4.2 cm (Mata Utu; Fig. 4) to 148.8 cm (Great Barrier Island; Fig. 6) (Table 1). At Nuku’alofa, which is the nearest tide gauge station to the volcano, a maximum tsunami amplitude of 123.0 cm was measured. It is quite important to note that some stations located more than 1,000 km from the source received significant maximum wave amplitudes, such as Ouinne (116.1 cm), Norfolk Island (128.0 cm), and Port Vila (117.2 cm) (Table 1). The large amplitude of 148.8 cm at Great Barrier Island and some other New Zealand stations is widely attributed to the contribution from both the Tonga tsunami and the Tropical Cyclone Cody (Liu and Tang, 2022). According to Fig. 8, all these stations are located to the south, southwest and west of the volcano, indicating that most of the tsunami’s amplitudes and energy were delivered in the aforementioned directions. In terms of duration of high-energy waves of the tsunami in tide gauge stations, the tsunami lasted at least half a day in all stations and oscillated up to more than two days in some stations such as Apia Upolu, Pago Pago, and Chatham Island (Figs. 4–6). Air pressure data at meteorological stations such as Nadi (Fig. 4), Noumea (Fig. 5) and Gisborne (Fig. 6) reveal that the atmospheric pressure waves arrived approximately 1.0–2.2 h before the arrival of tsunamis from the eruption-induced water displacements at the volcano.

Some coastal tide gauge stations, such as Fongafale, Lifou, Ouvea, Thio and Ouinne (Fig. 5) showed clear early tsunami arrivals compared to the arrival times expected from the eruption-induced water displacement waves propagating from the source. These early waves are most likely generated by atmospheric pressure waves as their onset coincides with the arrival times of the air pressure waves at some of these stations (Fig. 5). These are most likely local coastal oscillations inside bays and harbors triggered by ocean waves generated in the deeper ocean by the atmospheric pressure waves.

On DARTs, the maximum tsunami amplitudes were in the range of 3.6–21.4 cm for different DART stations (Table 1, Fig. 7). Similar to tide gauges, we observed that largest DART amplitudes were distributed towards the south, southwest and west of the volcano (Fig. 8).
Fig. 7. Tsunami waveforms of the 15 January 2022 Tonga tsunami as recorded on Deep-Ocean Assessment and Reporting of Tsunamis (DARTs). Locations of DART stations are shown in Fig. 1. The pink arrows show the approximate arrival times of the tsunami from the atmospheric pressure waves at each station, whereas the green arrows show those of the tsunami from the eruption-induced water displacement. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 8. Distribution of the zero-to-crest amplitudes of the 15 January 2022 Tonga tsunami on tide gauges (a) and DARTs (b). The black star represents the Hunga Tonga–Hunga Ha’apai (HTHH) volcano.
early arrivals of tsunami waves with atmospheric pressure wave origin are seen on DART records (Fig. 7).

5. Characteristics of the tsunami waves generated by atmospheric pressure waves

The generation mechanism of water waves generated by atmospheric pressure waves are discussed by Harkrider and Press (1967), who reported that volcano eruption pressure waves can excite sea waves. Harkrider and Press (1967) calculated the phase velocities for a coupled atmosphere-ocean model and showed that the first few dominant modes are "GR_0" (an atmospheric mode with phase velocity of approximately 312 m/s), "GW_0" (an ocean gravity mode with phase velocity \( \sqrt{gd} \), where \( g \) is gravitational acceleration and \( d \) is water depth; approximately 220 m/s for an ocean water depth of 5,000 m), followed by other atmospheric modes such as "GR_1", "GR_2", and "GR_3". The average speed of the atmospheric wave from the HTHH volcanic eruption is 325 m/s as suggested by barometric pressure data at weather stations.

For the 2022 Tonga tsunami, although the water waves generated by atmospheric pressure waves were not recorded clearly in all sea level stations, a few stations recorded early waves as compared to the arrival times of waves from eruption-induced water displacement source and thus are most likely generated by atmospheric pressure waves as confirmed by the air pressure data plotted for some stations (pink waveforms in Figs. 4–6) and by the TTT of air pressure waves (red contours in Fig. 1). On tide gauges, the water waves generated by atmospheric pressure waves registered a maximum amplitude of 8.0–19.0 cm and periods in the range 7–10 min (tide gauge stations Lifou, Ouvea, and Ouiine; Fig. 5). However, for DARTs, we see longer wave periods of approximately 30–60 min (Fig. 7). The maximum amplitudes of the DART water waves generated by atmospheric pressure waves are 4.2–15.7 cm (Fig. 7).

Looking at Figs. 4–7, it appears that tide gauge stations have been less sensitive to the air pressure waves as the oceanic wave amplitudes from the atmospheric pressure disturbance are almost of similar size or smaller than the noise level on most of the tide gauges (Figs. 4–6), while majority of the DARTs clearly revealed the arrivals of atmospheric pressure waves (Fig. 7). In fact, at DART stations amplitudes of ocean waves generated by atmospheric pressure waves are comparable to the amplitudes of ocean waves generated by eruption-induced water displacement, whereas at coastal tide gauges the amplitudes of ocean waves generated by atmospheric pressure waves are mostly negligible.
6. Spectral analyses and estimating tsunami source dimension

The purpose of this section is to estimate the dimensions of the tsunami source area using the spectral content of the tsunami observation waveforms; such estimates will be used in the next section to define our tsunami source scenarios. Spectra for the tide gauge and DART waveforms are given in Figs. 9 and 10, respectively. For tide gauges, we show the spectra for 16 stations out of the total 22 tide gauge stations; these are the stations that are located closer to the volcano site. Wavelet plots for both tide gauges and DARTs are generated and shown in Fig. 11. For tide gauges, we have been able to generate background spectra (spectra of part of the sea level data before the arrival of the tsunami at each station) (Fig. 9). However, due to unavailability of background data for DARTs, background spectra for DARTs are not presented (Fig. 10).

The spectra for tide gauges reveal multiple peak periods including (but not limited to) those at 4 min, 5 min, 6 min, 7 min, 12 min, 17 min, 19 min, 20 min, 21 min, 22 min, 28 min, 32 min, 34 min, 37 min, 43 min, and 51 min. The spectra field is crowded as tide gauges usually record a wide range of signals generated by global (oceanic basin), regional (e.g., bays and continental shelf) and local (e.g., ports and harbors) bathymetric features in addition to those from the tsunami source (Rabinovich, 1997; Rabinovich and Eble, 2015; Heidarzadeh and Satake, 2014; Heidarzadeh et al., 2018, 2019). Therefore, tsunami source signals are mixed with many other non-source signals. Hence, it is important to apply deep-ocean tsunami measurements for discovering tsunami source signals, where available, as such records are free from most of the aforementioned bathymetric features. Although there are techniques to discover tsunami source signals from tide gauge records, such as spectral ratio proposed by Rabinovich (1997), we do not explore them in this study because we have the deep-ocean measurements of this tsunami (i.e., DART records).

DART spectra (Fig. 10) reveal fewer spectral peaks relative to those of tide gauges. As we know from the previous section that signals at the period band of approximately 30–60 min are generated by the atmospheric pressure waves, we ignore such signals in the DART spectra (dashed pink bands in Fig. 10) because this study is primarily aimed at developing a source model for the part of the tsunami generated by water displacements at the volcano. By looking at DART spectra and excluding those peaks at 30–60 min, the remaining signals can be...
grouped into two period bands of 10–17 min and 4–7 min (Fig. 10). It is noted that both period bands can be seen in tide gauge spectra as well (Fig. 9).

Wavelet analysis (Fig. 11) reveals the changes of tsunami dominant periods over time. The areas with yellow or orange colors in Fig. 11 are those of higher tsunami energy and dominant periods. For example, at Ouinne (Fig. 11b), the dominant tsunami period is approximately 30–45 min at the beginning of tsunami arrival, and later gradually shifts towards shorter periods of 10–17 min. Wavelet plots further confirm that the initial signals at each station are at periods >30 min, which is due to the early arrivals of the sea waves generated by atmospheric pressure waves (Fig. 11). Consequently, tsunami energy is distributed at two channels of 10–17 min and 4–7 min. We conclude that the tsunami waves due to water displacements at the volcano show two peak period

Fig. 11. Wavelet analyses for the DART (a) and tide gauge (b) records of the 15 January 2022 Tonga tsunami. The white areas in the plots of NZF, NZK, NZD and D-55023 indicate time periods with no waveforms available for Wavelet analyses. The dashed vertical line indicates the approximate time of the eruption.

![Volcano sketch](image)

Fig. 12. Sketch showing the hypothetical initial elevation wave considered for modelling the 15 January 2022 Tonga volcanic tsunami. Here, $L$ is the characteristic length, and $a_M$ is the characteristic maximum water displacement (initial wave amplitude) of the tsunami source.
Fig. 13. Different initial source scenarios considered for modelling the 15 January 2022 Tonga tsunami. Additional information regarding these source scenarios are given in Table 3. Here, $L$ is the characteristic length, and $a_M$ is the characteristic maximum water displacement (initial wave amplitude) of the tsunami source.

Table 3
The tsunami source scenarios considered in this study for the 15 January 2022 Tonga volcanic tsunami. The volume in this table means the volume of the displaced water due to the volcano eruption.

| Name | Source length, $L$ (km) | Maximum initial amplitude, $a_M$ (m) | Volume ($m^3$) | $K$  | $\kappa$ |
|------|------------------------|-----------------------------------|----------------|-----|---------|
| S1   | 6                      | 30                                | $5.17 \times 10^8$ | 6.09 | 1.47    |
| S2   | 6                      | 60                                | $1.03 \times 10^9$ | 3.65 | 1.46    |
| S3   | 6                      | 90                                | $1.55 \times 10^9$ | 3.12 | 1.41    |
| S4   | 12                     | 30                                | $2.20 \times 10^9$ | 2.67 | 1.43    |
| S5   | 12                     | 60                                | $4.40 \times 10^9$ | 1.65 | 1.39    |
| S6   | 12                     | 90                                | $6.60 \times 10^9$ | 1.15 | 1.44    |
| S7   | 20                     | 30                                | $6.22 \times 10^9$ | 1.50 | 1.49    |
| S8   | 20                     | 60                                | $1.24 \times 10^{10}$ | 0.82 | 1.50    |
| S9   | 20                     | 90                                | $1.87 \times 10^{10}$ | 0.54 | 1.51    |

* The preferred source model.
bands of 10–17 min and 4–7 min.

Here, we use the peak tsunami periods to estimate the characteristic length \( L \) of the tsunami source area using the equation proposed by Heidarzadeh and Satake (2015b):

\[
L = \frac{T}{2} \sqrt{g \, d}
\]

where, \( L \) is the characteristic length of the tsunami source area, \( g \) is the gravitational acceleration, \( d \) is the average water depth around the tsunami source region, and \( T \) is peak tsunami period. Knowing that the water depth around the source region was \( d = 50–200 \) m, and applying the longer dominant period band of \( T = 10–17 \) min, the characteristic length of the tsunami source due to eruption-induced water displacement is estimated at 6.6–22.6 km.

7. Numerical modelling of candidate sources and the preferred source

The tsunami source of the January 2022 Tonga tsunami is comprised of two components: (i) The atmospheric pressure wave source, and (ii) The eruption-induced water displacement source at the volcano. In other words, the tide gauge and DART records of the tsunami are contributed by both atmospheric pressure waves and the water mass displacement at the volcano. We note that the term source model in this study is meant only for part of the tsunami source due to the second component, i.e., the water mass displacement at the volcano. As the atmospheric pressure waves travel faster than the oceanic gravity waves (Figs. 4–7), the first few phases recorded on the sea level observations are contributed by the atmospheric pressure waves, which cannot be reproduced by our source model.

For numerical modelling of the 2022 Tonga volcanic tsunami, we assume that the initial wave generated by the volcano mass movement is an elevation wave with a Gaussian shape (Fig. 12). In fact, in this approach, the dynamic generation process is simplified into a static source. Several authors have shown that such a simplification has negligible impacts on the entire tsunami life and is therefore a valid method, although its effects might be important in the very near-field (e.g., Synolakis et al., 2002; Tappin et al., 2008; Heidarzadeh and Satake, 2017; Heidarzadeh et al., 2020a,b; Grilli et al., 2021). Two initial wave parameters are considered in our modelling approach (Fig. 12) namely the characteristic length of the initial tsunami source \( (L) \) and maximum initial wave amplitude \( (a_0) \). We note that Fig. 12 is a hypothetical and
simplified representation of the Tonga tsunami source, and it is likely that the real tsunami source was more complicated than what shown in Fig. 12. However, such simplification does not introduce large errors in our study because we compare the simulated waveforms with the observed ones to validate the tsunami source.

To estimate the source of the tsunami, we apply a trial-and-error approach by taking into account the dimension of the source estimated in the previous section and comparing the simulated waveforms with the observed ones to validate the tsunami source.

To estimate the source of the tsunami, we apply a trial-and-error approach by taking into account the dimension of the source estimated in the previous section and comparing the simulated waveforms with the observed ones to validate the tsunami source. Based on the results of spectral analyses and estimates of initial tsunami source dimensions, we consider nine candidate source models by varying \( L \) and \( a_M \) (S1–S9; Fig. 13) with initial Gaussian elevation shapes, lengths of \( L = 6.0–20.0 \) km, and maximum initial amplitudes of \( a_M = 30.0–90.0 \) m (Table 3, Fig. 13). Tsunami modelling are performed for all nine models and the simulated waveforms are compared with the observations at DART stations (Fig. 14). To evaluate the performance of different source scenarios in reproducing the tsunami observations, two parameters \( K \) and \( \kappa \) are calculated for each source model (Table 3). Among these nine candidate models, the best one is model S6 as it gives the closest \( K \) value to one as well as a suitable \( \kappa \) value. Therefore, our modelling shows that the tsunami source most likely was 12 km long with maximum amplitude of 90 m (model S6 in Table 3 and Fig. 13). The volume of the displaced water due to the source model S6 is \( 6.60 \times 10^9 \) m\(^3\) (Table 3). Although there is no real measurement of the initial tsunami displacement above the volcano, our source model (i.e., model S6) is a realistic estimate of the tsunami source because it is validated using the actual tsunami measurements at DART locations.

Tsunami propagation snapshots due to the best source model (i.e. S6) are given in Fig. 15, whereas the maximum tsunami amplitudes at each grid point during the entire simulation time is presented in Fig. 16. As expected, our best source model (i.e., S6) arrives with 1–2 h delays at DART stations (Fig. 14) as our source model is only for the part of the Tonga tsunami generated by the gravity waves due to water displacement. We discussed in previous sections that the first few phases on DARTs and tide gauges are due to atmospheric pressure waves (Figs. 4–7), which cannot be reproduced by our source model. Apart from the first few phases, our best source model (i.e., model S6) successfully reproduces the later phases (Fig. 14). Tsunami propagation snapshots reveal two different propagation patterns towards the east and west of the volcano (Fig. 15); the wavefield appears to be crowded with shorter waves to the west, which is attributed to several wave reflections due to the presence of numerous islands and seamounts, making a semi-enclosed basin between Tonga islands and Suva Viti/Lautoka (Figs. 1 and 15). To the east, the tsunami waves freely travel with distinct wavefronts as the ocean is deeper and fewer islands exist in this side (Figs. 1 and 15). According to Fig. 16, maximum tsunami
amplitudes (and energy) are concentrated in the semi-enclosed basin between Tonga islands and Suva Viti/Lautoka. To the south, beams of high-amplitude tsunami waves are directed towards the coasts of New Zealand.

8. Conclusions

We studied the 15 January 2022 Tonga volcanic tsunami, which was generated by the volcanic eruption of the Hunga Tonga–Hunga ‘apai volcano and killed at least five people, and proposed a source model for its eruption-induced water displacement generation mechanism. The main findings are:

- Two mechanisms contributed to the 2022 Tonga volcanic tsunami comprising, (i) Atmospheric pressure waves, and (ii) Gravity waves generated by water mass displacement due to the eruption.
- The maximum overall (i.e., due to both atmospheric pressure waves and water mass displacement at the volcano) zero-to-crest coastal tsunami amplitudes on tide gauges were in the range of 4.2–14.8 cm at different tide gauges. The largest amplitude of 14.8 cm was recorded at the Great Barrier Island along the coast of New Zealand, which is likely due to both the Tonga tsunami and the Tropical Cyclone Cody.
- Mid-ocean instruments (DARTs) registered maximum overall (i.e., due to both atmospheric pressure waves and water mass displacement at the volcano) tsunami amplitudes of 3.6–21.4 cm.
- Fourier and wavelet analyses of the tsunami sea level records guided us towards extracting the dominant tsunami periods due to the eruption-induced water displacement generation mechanism, which are 10–17 min and 4–7 min.
- The tsunami waves generated by atmospheric pressure waves had a period of 7–10 min and amplitude of 9–19 cm on coastal tide gauges; the corresponding values for DARTs were 30–60 min and 4.2–15.7 cm.
- Based on the numerical modelling of nine candidate source models, we estimated that the eruption-induced water mass displacement source of the January 2022 Tonga tsunami had a characteristic initial length of 12 km, a maximum initial amplitude of 90 m, and a volume of $6.60 \times 10^5$ m$^3$.

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Availability of data and materials

The tide gauge data used in this research are provided by the Sea Level Station Monitoring Facility of the Intergovernmental Oceanographic Commission (IOC) of the United Nations (http://www.ioc-sea levelmonitoring.org/index.php). The DART (Deep-Ocean Assessment and Reporting of Tsunamis) data are provided by the United States National Oceanic and Atmospheric Administration (https://nctr.pmel.noaa.gov/Dart/) and New Zealand GeoNet services (https://www.geonet.org.nz/tsunami/dart). The seismic data are from Wilber 3: The Incorporated Research Institutions for Seismology (IRIS; https://ds.iris.edu/wilber3/find_event). Atmospheric pressure data are provided by Fiji Meteorological Service (https://www.met.gov.fj/) for Fiji data, National Institute of Water and Atmospheric Research (https://niwa.co.nz/) for New Zealand data, and Météo France - Direction Intérimonale de la Nouvelle Calédonie et de Wallis et Futuna for French Polynesia and New Caledonia data.

CRediT authorship contribution statement

Mohammad Heidarzadeh: conducted tsunami waveform and spectral analyses and drafted the manuscript. Aditya Riadi Gusman: performed tsunami simulations. Takeo Ishibe: conducted seismic analysis. Ramtin Sabeti: compiled coastal damage of the tsunami. Jadranka Sepić: prepared and analyzed atmospheric pressure data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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