



Characterizing sea level and barometric disturbances in the Caribbean and adjacent regions from the Hunga Tonga-Hunga Ha'apai 2022 eruption

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ABSTRACT

The Hunga Tonga Hunga Ha'apai eruption of January 15th, 2022, was a rare geological event, resulting in atmospheric pressure waves being recorded around the world, along with sea level fluctuations. This research aims to analyze the tsunami and pressure waves observed in the Caribbean and adjacent regions, which were generated by this eruption. These kinds of perturbations are uncommon and have not been seen in many occurrences, let alone with global implications. Modern instrumentation in the Caribbean and adjacent regions, including both barometers and sea level stations, provided a unique opportunity to observe and analyze this event. A comprehensive review of the observations recorded in the Caribbean and adjacent regions linking the barometric observations to sea level perturbations, including observations of the lead/lag relative to the barometric pressure spikes and the frequency content of observable sea level perturbations, will be shown in this study. For instance, most of the stations in this study recorded six barometric spikes, of which the first two generated a significant sea level observation. Circumstances complicating observations, such as interference from factors, e.g. a strong cold front and lack of standardization, will also be discussed. This study, which will integrate observations from across the Caribbean and adjacent regions, aims to better understand the nature of this unique event and how it was observed in the region. As such, this research can offer insight into the factors that may influence volcanic tsunamis, which is invaluable for developing tsunami warning and response protocols.

Keywords: Pressure waves, Volcanic tsunamis, Hunga-Tonga, Lamb waves, Caribbean

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INTRODUCTION

The most recent Hunga Tonga Hunga Ha'apai (HTHH; Figure 1) eruptive sequence began on December 19th, 2021, with a succession of explosive

eruptions (Gupta et al., 2022). The paroxysmal phase of the eruption took place on January 15th, 2022, with an explosivity index estimated VEI ~6 (Poli and Shapiro, 2022) and the energy estimates have ranged from 25 (Pakoksung et al., 2022) to over 58 megatons of TNT (Kulichkov et al., 2022). The explosions generated a broad range of waves in the atmosphere, including acoustic and gravity waves that reached the ionosphere. The acoustic-gravity waves were detected on many devices, such as infrasound stations, surface pressure

recorders (Kubota et al., 2022; Kulichkov et al., 2022), GNSS receivers (Astafyeva et al., 2022; Zhang et al., 2022), seismometers (Matoza et al., 2022), atmospheric infrared sounders (Wright et al., 2022), and hydroacoustic hydrophone stations (Le Bras et al., 2022). Explosions started at ~04:05 UT on January 15th, 2022 (Astafyeva et al., 2022). From 04:05:54 to 04:54:27 UT, five main explosions were recorded during the paroxysmal phase, in which the second one at 4:18:10 UT was the most powerful one (Astafyeva et al., 2022).

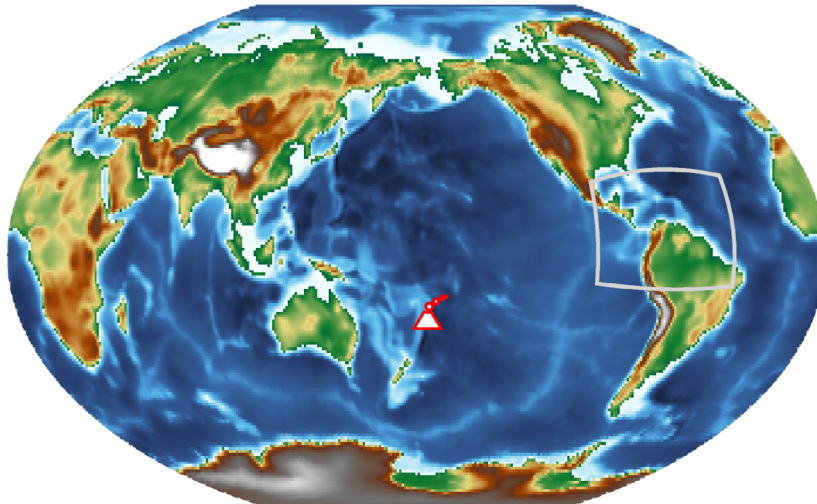


Figure 1. Global bathymetry and topography map. The location of the Hunga Tonga Hunga Ha'apai volcano is indicated by the red triangle. The grey square indicates the general area of the locations of stations from the Caribbean and adjacent regions used in the study (Figure 3).

The eruption was associated with tsunamis that were observed both in the near and far field (Borrero et al., 2022; Carvajal et al., 2022). In the near field, the first tsunamis of January 15th, 2022, were observed before the largest explosion at ~4:18 UTC (Borrero et al., 2022), and they were followed by other waves generated around 4:26 UTC. The largest wave to hit Tongatapu was observed soon after 5:00 UTC, and later tsunamis continued until ~9:00 UTC. A maximum run up of 19 m was measured by Borrero et al. (2022) on the northwestern coast of Tongatapu, and 20 m on the southeastern coast of Nomuka Island, 65 km SE and NE from the HTHH volcano, respectively. Inundation distance varied from one site to another, ranging from less than 100 m to more than 1,000 m.

The tsunami caused the displacement of more than 1,500 people as well as an estimated \$90.4

million in damages (GFDRR, 2022). The tsunami also caused damages in Fiji, Hawaii, Chile, Costa Rica, California, Japan, Russia, and New Zealand, and an oil spill in Peru (GFDRR, 2022). In the far field, leading tsunami waves arrived earlier than expected for a “usual” tsunami freely propagating away from its source in the deep ocean: two hours earlier in Japan, about one hour earlier in Costa Rica, two to five hours earlier in Chile, 15 hours earlier in the Caribbean and Italy (Carvajal et al., 2022; Chacón-Barrantes et al., 2023; Imamura et al., 2022; Omira et al., 2022). Wave heights up to 3 m were observed in northern Chile, 2 m in Peru, 2 m in Mexico, 1.2 m in Japan, 1.3 m in Southern California, 0.8 m in Hawaii, 1.2 m in Vanuatu, 0.6 m in American Samoa (Carvajal et al., 2022), and 0.97 m in Costa Rica (Chacón-Barrantes et al., 2023). The tsunami was

also recorded in the Indian and Atlantic oceans, the Caribbean Sea, and the Mediterranean Sea.

This event stands out from volcanic tsunamis with a very localized impact that does not typically generate far-reaching waves. The propagation of the leading waves in the world oceans at ~ 310 m/s is concordant with the propagation of the Lamb mode of the acoustic-gravity waves produced by the explosions (Gusman et al., 2022; Kubota et al., 2022; Omira et al., 2022; Yamada et al., 2022). The atmospheric forcing lasted from hours to days, showing very little energy dissipation (Kubota et al., 2022). Consequently, the tsunami lasted much longer compared to earthquake-induced tsunamis.

In Central America, between the Pacific Ocean and the Caribbean Sea, the tsunami “jumped” over land in a few minutes (Chacón-Barrantes et al., 2023) with a small loss of wave height on the western Caribbean coasts, and it got re-excited in the Antilles (Omira et al., 2022; Ramirez-Herrera et al., 2022). Many Caribbean stations detected small amplitude waves about 12 hours after the eruption, which does not correspond to the arrival time of a tsunami wave propagating from HTHH (Carvajal et al., 2022). This early arrival could be due to a different tsunami mechanism generating the first perturbations in sea level, being driven by fast acoustic waves instead of the main explosion (Lynett et al., 2022; Santellanes et al., 2023). For example, a Puerto Rico station in Mayagüez detected a tsunami signal at 15:30 UTC on January 15th, 2022, whereas the Tide Tool calculations run at the Puerto Rico Seismic Network (PRSN) estimated a tsunami arrival time from a water column displacement at 07:22 UTC on January 16th, 2022. In addition to these sea level disturbances, atmospheric pressure anomalies were detected at multiple barometric stations throughout the Caribbean and adjacent regions, although they were variable in signal strength, which in some cases coincided with the sea level disturbance (Personal communication between authors). Other studies (Omira et al., 2022) have demonstrated that this tsunami was not only generated by these atmospheric pressure disturbances but was also reinforced by it, causing this tsunami to travel faster,

last much longer, and reach greater distances than expected. Observations by Omira et al. (2022) and Yamada et al. (2022) of the event in the Pacific interpreted the second tsunami wave train because of resonant ocean-gravity waves with acoustic-gravity waves (similar to a Proudman resonance). The air-sea coupling is possible by matching the speeds of the atmospheric-gravity waves and the ocean-gravity waves at ~ 200 m/s, corresponding to the typical velocity of a tsunami wave in the deep ocean. Figure 2 shows the air-sea coupling behavior of this tsunami in the Caribbean and adjacent regions based on a model established by Sepúlveda et al., 2023 (for full model, please see [Figure S1](#)). The model is compared to meteorological satellite near-infrared band data from GOES ($10.3 \mu\text{m}$) and METEOSAT ($10.8 \mu\text{m}$), which are interpreted to measure the perturbation in temperature due to the change in pressure caused by the Lamb wave. The model in Figure 2(B) includes all variables that may contribute to the dissipation of the Lamb Wave. Figure 2(C) shows the Lamb wave-generated tsunami's behavior and the observed wave energy differences in the different ocean basins. This resonance is not expected in shallow waters such as near a continental platform and coral reefs. In contrast, it is amplified in the deepest abyssal plains and trenches, which is in clear contrast with what happens during other tsunamis. The described behavior was also observed in our study in the data from Puerto Rico, in which the Puerto Rico trench on the North of the island influenced the wave in the form of resonance as studied by Carvajal et al., 2022. A similar phenomenon occurred during the Krakatoa volcano eruption in 1883, which also resulted in a worldwide tsunami (Ewing and Press, 1953; Pelinovsky et al., 2005; Harkrider and Press, 1967). Moreover, observations from this study indicate that changes in coastline morphologies and bathymetry can lead to variations in the tsunami signal, resulting in fluctuations in the arrival times of the tsunami or barometric pressure spikes at nearby stations. Other authors have also identified this phenomenon in data collected from sites along the same coastline in Australia (Davies et al. 2024).

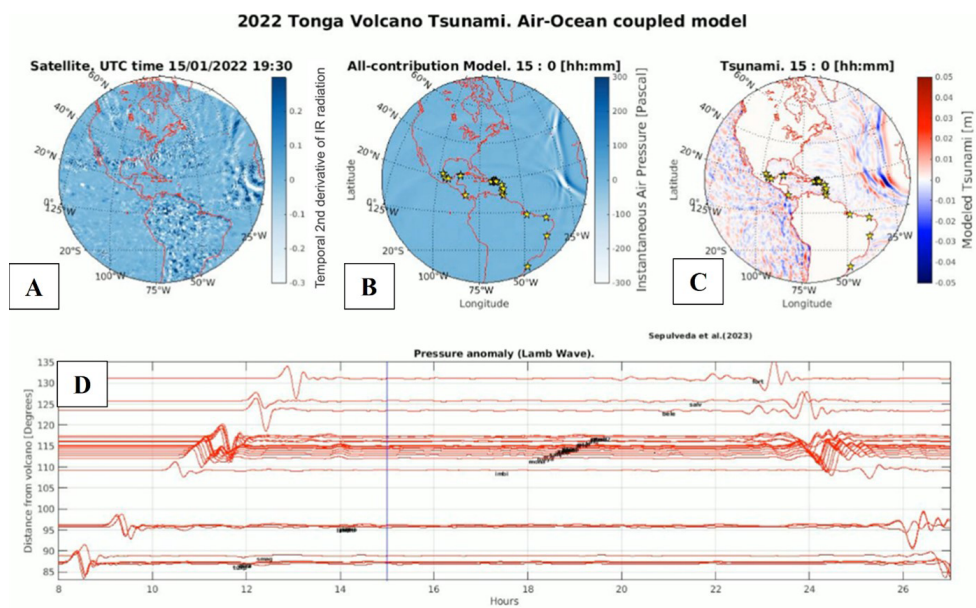


Figure 2. Model of the air-coupled tsunami showing barometric pressure data (lower panel D) from the Caribbean and adjacent region stations (indicated by yellow stars) which were used in this study. (A) Satellite image data was used to measure the radiation of the Lamb wave (barometric pressure). (B) Numerical model of the Lamb wave including all variables that contribute to the modification of the propagation of the wave, such as wind and topography. (C) Model of the Lamb wave-generated tsunami, showcasing the differences in wave energy between the Pacific Ocean and the Atlantic Ocean, as well as in the Caribbean Sea. The blue line in (D) indicates the timestamp of the Lamb wave in A-C (Adjusted from Sepulveda et al., 2023).

The spikes and disturbances are unusual because they have not been seen in modern times, let alone with global effects. As a result, this study aims to characterize the tsunami waves and their possible relation to observed spikes in barometric pressure related to the HTHH eruption as another goal is to contribute to observational data from Puerto Rico, US Virgin Islands, Costa Rica, Mexico, Lesser Antilles, and Brazil that, when combined with other data resources from the Caribbean and around the world, can be used to place the wave behavior in a larger context; in short, to determine how this phenomenon was shown in the Caribbean and adjacent regions. Understanding the mechanism behind this eruption and volcanic tsunamis has the potential to improve tsunami early warning systems that are invaluable in the development of tsunami preparedness and response protocols.

Note that the current early warning systems for tsunamis do not consider volcanic eruptions as possible sources of tsunamis (Paris, 2015). Volcanic tsunamis are not as common as tsunamis triggered

by earthquakes, but they are also deadly, especially considering there was no regional warning system or standardized protocol in places that consider this type of tsunami source for the Pacific. After the events of HTHH in 2022, a new interim protocol as part of the Pacific Tsunami Warning and Mitigation System was designed to account for this significant gap (IOC-UNESCO, 2022). For the Caribbean, tsunami warning systems began to be developed in 2015 as established by the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (CARIBE-EWS) (IOC-UNESCO, 2023). However, it was not until recently that a draft memorandum of understanding was established between the regional Tsunami Service Providers (TSPs) and volcano observatories (IOC-UNESCO, 2023; Clouard et al., 2024). This study also emphasizes the importance of accessible sea level data and the need for an updated early warning system to be implemented, as they are the only means for such types of tsunamis to be properly identified and to successfully estimate the arrival time of the wave to save lives.

METHODS

This is an observational study based on the characteristics of the tsunami signals and barometric pressure spikes associated with the Hunga Tonga eruption reflected on stations across the Caribbean and adjacent regions, including Puerto Rico (PR), the U.S. Virgin Islands (USVI), Lesser Antilles, Costa Rica, Mexico, and Brazil (Figure 3). Since the tsunami had wrapped around the world about six times (Zhang et al., 2022), multiple barometric pressure spikes were recorded in various regions. Because of this, the data to study this event were collected from January 14th to January 21st, 2022, to account for all the pressure spike arrivals. Regarding PR and the USVI, the barometric pressure data were collected from stations on the National Oceanic and Atmospheric Administration (NOAA) tides and current database (tidesandcurrents.noaa.gov/map/index.shtml). The specific NOAA stations used for this study include Arecibo (Station ID: 9757809), Culebra (Station ID: 9752235), Mayagüez (Station ID: 9759394), San Juan (Station ID: 9755371) and Vieques (Station ID: 9752695), as well as Charlotte Amalie (Station ID: 9751639), Limetree (Station ID: 9751401), Lameshur (Station ID: 9751381), and Christiansted (Station ID: 9751364). Given the barometric pressure data for both Puerto Rico and the USVI, the only data available were in six-minute samples which may affect the resolution and precision of the peak but should not result in a major interference to the observations made in this study. For Costa Rica, the barometric data were collected from Santa Cruz Meteorological Station (SCMS) in the North Pacific Coast, with a sampling rate of 30 s. In the case of Brazil, the data were collected from the Rede Maregráfica Permanente para Geodésia (RMPG) repository, which is the Brazilian Permanent Tidal Network for Geodesy, in a sampling rate of one hour. For Mexico, the data were collected from the repository Servicio Mareográfico Nacional (National Sea Level Monitoring Service, www.mareografico.unam.mx), which belongs to the Geophysics Institute of the National Autonomous University of Mexico (UNAM) in a 10-minute sampling rate. Finally, in the case of the Lesser Antilles, in Martinique and Guadeloupe, the barometric data were collected for

Lamentin and Raizet weather station, respectively, from MeteoFrance, the French MetService, with a one-min sampling rate and for the north of the island from the Geoscope seismic station Morne la Rosette, Martinique, France (FDFM), with a one-second sampling rate. For the other territories, as there were no barometric data available near the tide gauge stations, the FDFM station data were used as a proxy given its proximity by great circle distance. Note that the differences in sampling rates pose a challenge to the study when attempting to compare the observations from each region, as well as in the precision of the observed peak in barometric pressure. The data recovered from these barometric stations were used to identify the specific arrival time (based on the highest amplitude or peak), millibar, and polarity of each barometric pressure spike associated with the eruption of HTHH.

The sea level data for all countries and territories in this study were recovered from the Intergovernmental Oceanographic Commission (IOC) repository (ioc-sealevelmonitoring.org/list.php) in one-minute sampling rates. For Puerto Rico, data were also collected from the PRSN repository and for Martinique from the Service Hydrographique et Océanographique de la Marine (<https://data.shom.fr/donnees/refmar/>). The sea level stations that were used for this research include Arecibo (Station ID: arac), Culebra (Station ID: cule), Mayagüez (Station ID: maya), San Juan (Station ID: sanj), and Vieques (Station ID: vieq) in Puerto Rico, as well as Charlotte Amalie, St. Thomas (Station ID: amal), Lameshur Bay, St. John (Station ID: lame), Christiansted, St. Croix (Station ID: stcr) and Limetree, St. Croix (Station ID: lime) in the USVI. Regarding the Arecibo and Culebra stations in Puerto Rico, six-minute sample data were used since these stations seemed to have problems with the one-minute instrument or an issue with satellite communication. In turn, sea level data for the stations in the USVI were also collected from the Center for Operational Oceanographic Products and Services (CO-OPS, 2007) website under Tsunami Capable Tide Stations. For Costa Rica, sea level data from the Limon station (Station ID: limo) were employed. For these stations, most of the datasets available were also in a six-minute sampling rate. Because of this, the frequency analysis for these stations in which six-minute data were used may

be affected in terms of uncertainty. For Mexico, data from the stations of Tuxpan (Station ID: tuxp), Veracruz (Station ID: vera), Alvarado (Station ID: alva), Sanchez Magallanes (Station ID: smag), Isla Mujeres (Station ID: imuj), and Puerto Morelos (Station ID: pumo) were recovered. Regarding the West Indies, the following stations were used: calq in Saint Vincent, gale in Trinidad and Tobago, pric in Grenada, ptmd2 in Dominica, and stlu, stlu2 and stlu4 in Saint Lucia, Precheur (Station ID: prec),

Le Robert (Station ID: lero) and Fort-deFrance (Station ID: ftfr) in Martinique and Deshaies (Station ID: desh) and Pointe-a-Pitre (Station ID: ptpt) in Guadeloupe. Finally, the data employed for Brazil corresponds to the stations in Belém (Station ID: bele), Fortaleza (Station ID: fort), Imbituba (Station ID: imbi), and Salvador (Station ID: salv). After recovering the sea level data, the raw data were plotted to identify the tsunami arrival times (based on the first break or deviation in data) in each station.

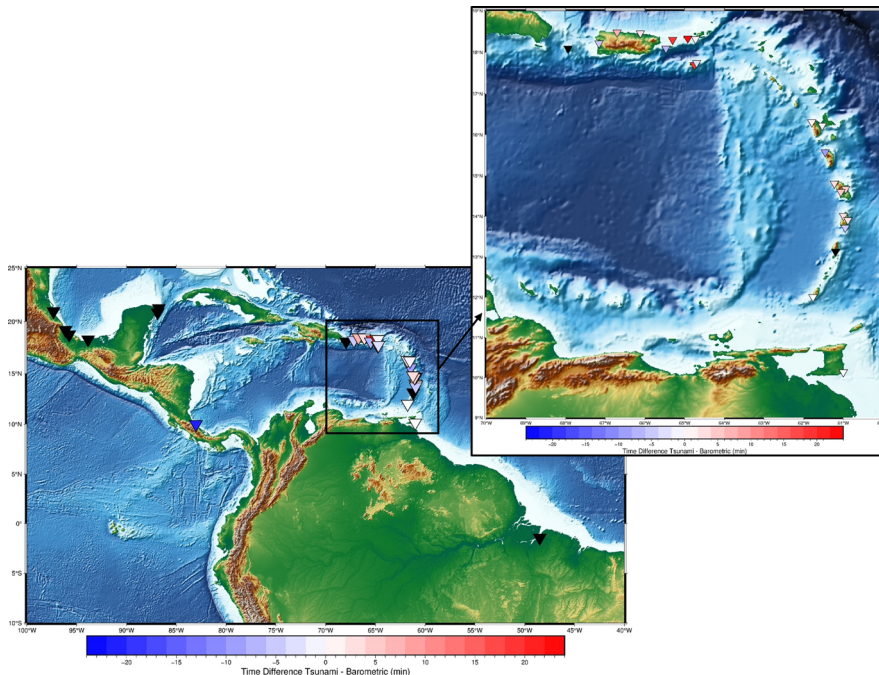


Figure 3. Map of co-located sea level and barometric stations from the Caribbean and adjacent regions stations included in the investigation (Fortaleza and Imbituba of the Brazilian stations are not shown, given their location, to maintain the region of dense stations visible). Black triangles indicate stations with no observation of a tsunami or barometric signal for the first wave. White triangles indicate stations with an observed delayed tsunami arrival beyond 20 minutes. Red triangles indicate stations where the barometric pressure spike preceded the tsunami's arrival, while the contrary is true for the blue triangles. The topography of the map is from the ETOPO1 model. Generated by PyGMT.

Firstly, a 2nd order Butterworth high pass filter with a corner frequency of 0.00015Hz (~111-minute period) was used to remove the tides, retaining periods shorter than approximately two hours and the tsunami signal. The mean was also removed to center the water level readings at zero, given that some stations could have a constant offset. Frequency and sea level plots were used to record the dominant frequency as well as the maximum amplitude, measured as half amplitudes: zero to peak or zero to

trough of each tsunami arrival. The difference between the barometric pressure spike and the tsunami signal arrival times was calculated. The arrival times for the tsunami signal were identified based on the first deviation in sea level data, whereas the arrival times for the barometric pressure spikes were selected based on the peak in data or highest amplitude (positive or negative). In addition, frequency analysis of each pressure spike relative to sea level was done using the resulting plots.

RESULTS

First, note that this was a very rare event, and as such, there is no established approach on how to classify and subsequently analyze this phenomenon. From the sealevel station network in the Caribbean and adjacent regions (composed of 64 coastal and five Deep Ocean Assessment and Reporting of Tsunamis (DART) stations), only 42 were online and collecting data while the rest were down or not uploading data in real-time during January 2022 (Figure 4). In some cases, such as Limón in Costa Rica, the station was operational but not transmitting data. Additionally, Figure 5 shows that the observed tsunami arrival times did not match the expected travel times for an ocean-traveling tsunami generated at HTHH. The stations included in this study are in Mexico, Costa Rica, Puerto Rico, the USVI, Brazil, and the Lesser Antilles (Chacón-Barrantes et al., 2023; Dourado et al., 2022; Ortiz-Huerta and Ortiz, 2023; Sostre-Cortés et al., 2022). The pressure wave was recorded in all the stations above, although with varying intensities. In most of the Caribbean stations used for this study, six successive pressure spikes were recorded (Figure 6), spanning a total period of approximately 90 hours (based on the Tuxpan and Veracruz stations, which were the first and last to record the 1st and

6th pressure spike, respectively). More specifically, the Puerto Rico stations had a period of about 84 hours, the stations from the French Antilles had a period of about 83.25 hours and for Costa Rica the period was about 87 hours. The stations in the rest of the Lesser Antilles and the USVI either did not record all spikes in barometric pressure, or the data hindered a precise observation. Therefore, this article will remain focusing on the first two barometric pressure spikes and corresponding tsunami arrival times (Table 1). In summary, the arrival time of the first spike in barometric pressure was closely followed by the first tsunami arrival time in the case of Limón, Costa Rica, with a difference of 16 minutes; Martinique and Guadeloupe, with a mean difference of 2.4 minutes; Puerto Rico, with a mean difference of 7.6 minutes, and the USVI with a mean difference of 11.25 minutes, while it varied significantly for the other locations within this study (Figures 7 and 8). The differences in arrival times for the second pressure spike and tsunami wave varied significantly from the first, recording much higher average differences: 83 minutes for Puerto Rico, 51 minutes for the USVI, and 19.6 minutes for Martinique and Guadeloupe. It was also observed that the first two pressure spikes were positive in wave polarity. This is an indication

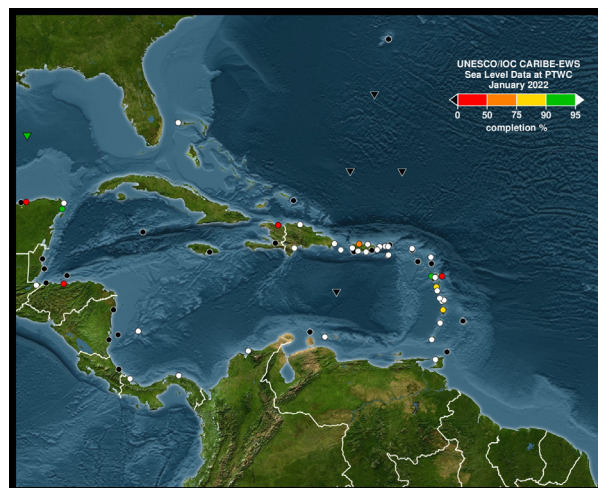


Figure 4. Map of sea level stations from the Caribbean and adjacent regions and the status of data availability at the Pacific Tsunami Warning Center (PTWC) for January 2022. Triangles indicate Deep-ocean Assessment and Reporting of Tsunamis (DART) buoy stations and circles indicate tide gauge stations. Completion percentage refers to the percentage of data received within 15 minutes of recording. Black stations indicate stations that are down or not uploading data in real time, and white stations indicate that the station is fully operational and transmitting data. During the month of January 2022, less than half of the stations were operational (42 out of 69 stations).

that the pressure wave induced by the explosion was pushing or compressing the surrounding air, resulting in a positive polarity. Additionally, a preliminary model, which assumed a 307 miles per hour velocity for the traveling pressure spike, was used to correlate the accuracy of the observed arrival times. This model was primarily reliable

for the first pressure spike but was still helpful in comparing the second pressure spike estimates. The observed arrival time of the air pressure spikes was also coincidental with the modeled estimated arrival times (Table 1), with differences between one to six minutes in most of the stations within this study.

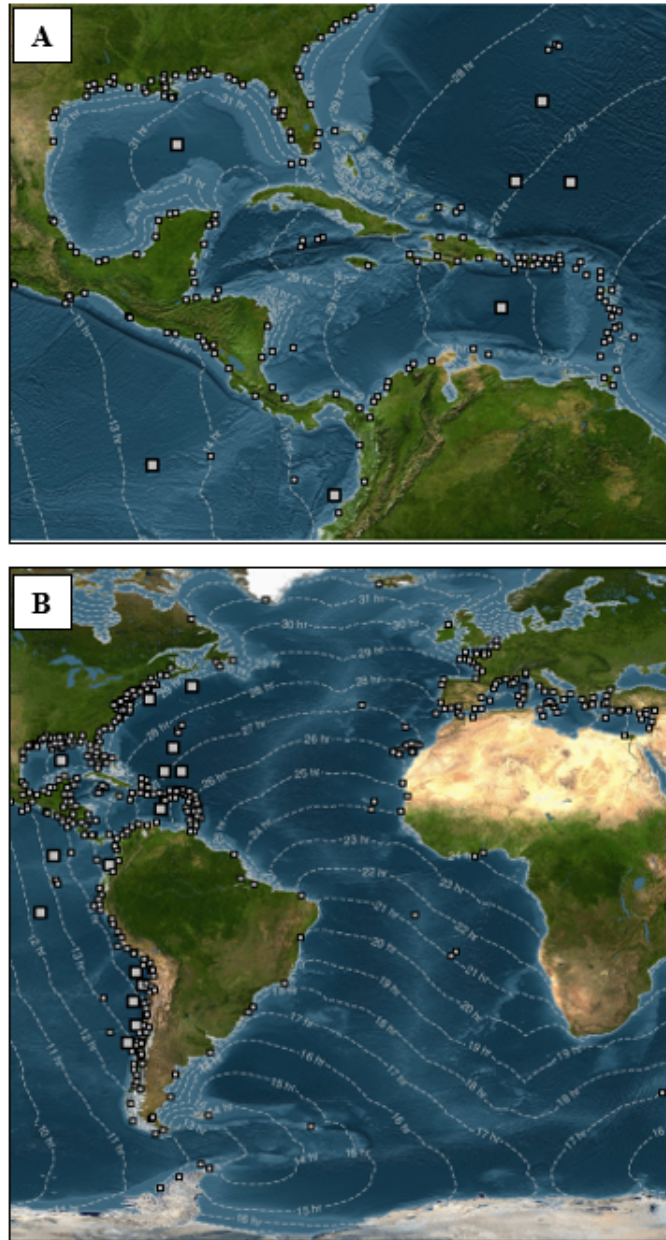


Figure 5. Expected tsunami travel times of (A) the Caribbean Sea and (B) the Atlantic Ocean from the first wave of the tsunami. Dashed lines indicate the travel time of a typical tsunami (i.e. not coupled with an atmospheric Lamb wave). Squares indicate the location of DART stations and circles indicate the location of coastal tide gauge stations. Maps were generated using Tide Tool 3.12.

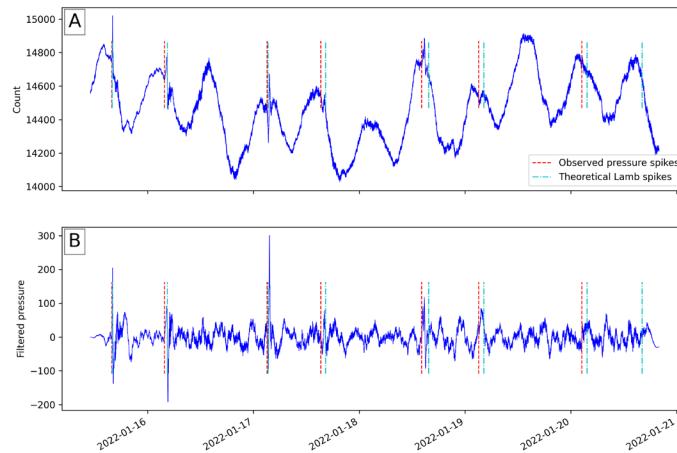


Figure 6. Barometric pressure data recorded at 1Hz from 2022-01-15 12:00 until 2022-01-21 00:00 at Geoscope FDFM station in Morne la Rosette, Martinique, France. (A) Raw data, (B) Filtered data between 3.10-2 and 5.10-5 Hz. The observed pressure spikes are the red vertical dashed lines and cyan dashed-and-dotted vertical lines are the theoretical spikes, using the velocity of 310 m/s from Fujii & Satake, 2024.

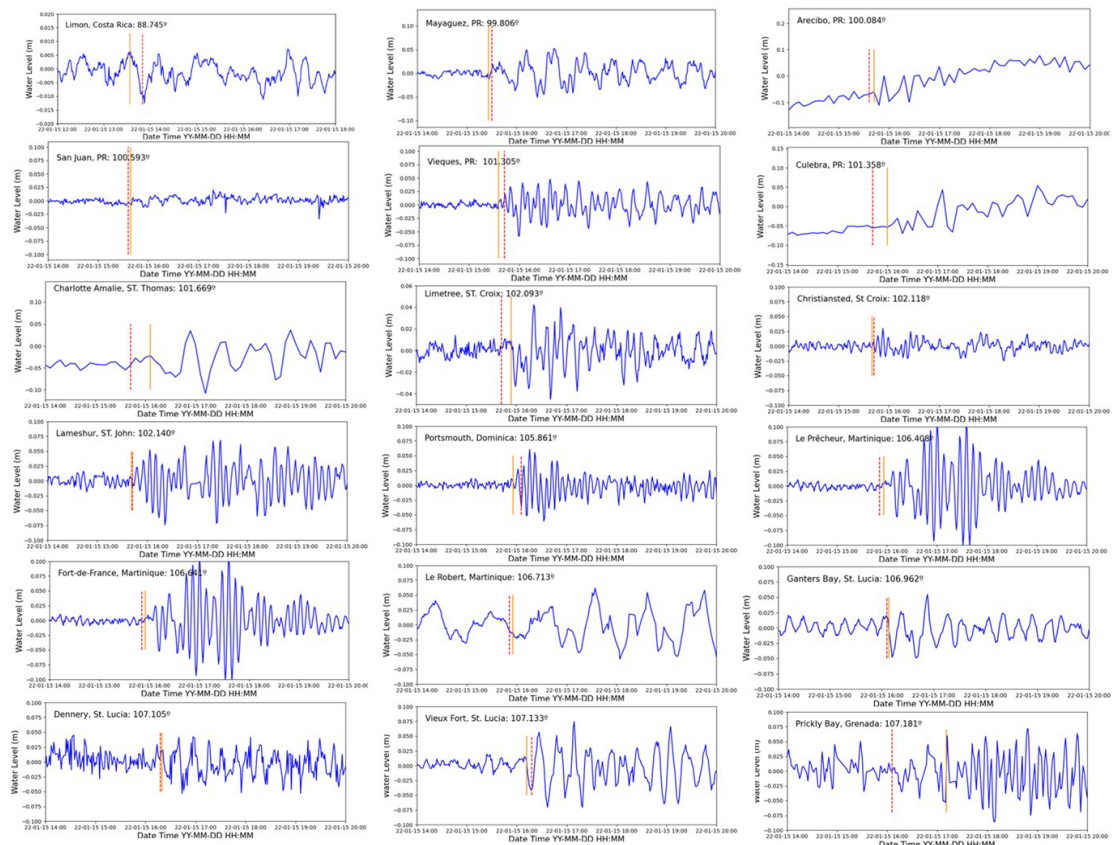


Figure 7. Filtered sea-level (blue line) data in meters of the first observed barometric pressure spike (dashed red line), marking the arrival of the first tsunami wave (solid orange line). The plots shown here help visualize the neatly coincident arrival of the pressure spike and the tsunami. Larger amplitudes in sea level are also seen after the arrival of the pressure spike. The data were highpass filtered to remove the tides, and the mean was removed to permit consistent spacing. The data were also de-spiked when necessary. Times are in UTC. For a summary of all observed pressure spikes and tsunami arrival times, see Table 1.

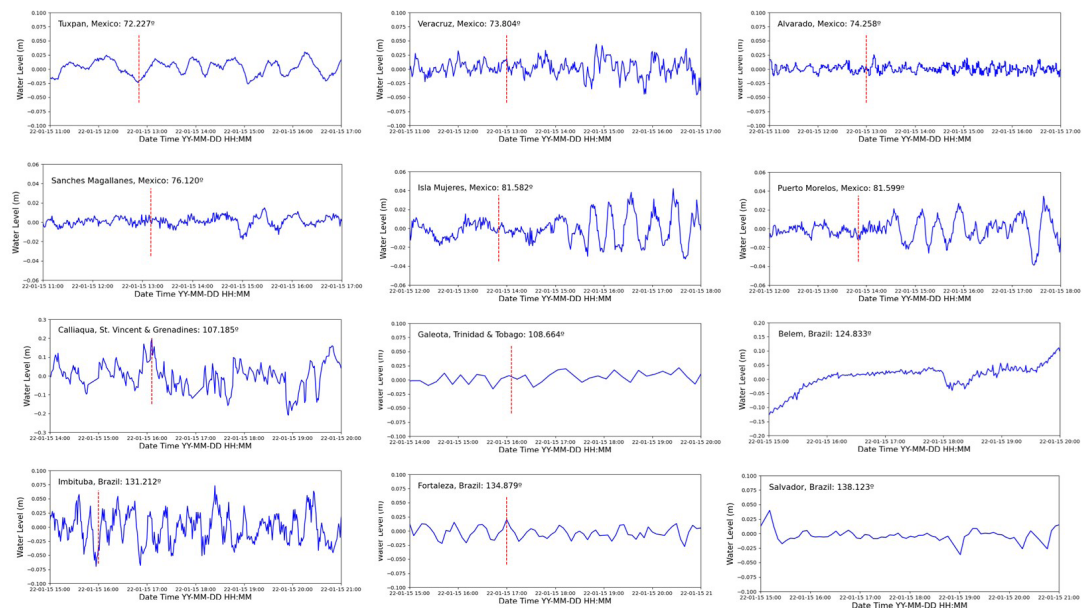


Figure 8. Filtered sea level (blue line) data of the first observed barometric pressure spike (dashed red line). These are stations in which no tsunami signal was observed near the pressure spike. Regarding Mexico, inclement weather generated significant noise in the data, preventing the observation of a possible tsunami signal. For Brazil, the barometric pressure spike was likely affected by the topography and the extensive data sampling rate, obstructing a clear observation. The data were highpass filtered to remove the tides, and the mean was removed to permit consistent spacing. The data were also de-spiked when necessary. Times are in UTC. For a summary of all observed pressure spikes and tsunami arrival times, see Table 1.

Table 1. Observed barometric pressure spike and tsunami signal arrival times for all stations included in the investigation. Modeled pressure spike arrival indicates the estimated arrival time of the pressure spike at a given station calculated from a preliminary model, assuming a travel velocity of 307 miles per hour. Cells with a hyphen indicate no observation of a signal in the data.

Country/Territory, Station (Lat, Lon)	Observed pressure spike date (YYYY-MM-DD)	Observed pressure spike arrival (UTC)	Modeled pressure spike arrival (UTC)	Observed tsunami arrival (UTC)	Difference in arrival times (sea level - pressure spike)
Mexico, Tuxpan (20.9638, -97.3286)	2022-01-15	12:50	12:56	-	-
	2022-01-16	08:00	07:46	-	-
Mexico, Veracruz (19.1922, -96.1235)	2022-01-15	13:00	12:59	-	-
	2022-01-16	07:00	07:44	-	-
Mexico, Alvarado (18.766,- 95.7559)	2022-01-15	13:00	-	-	-
	2022-01-16	07:30	-	-	-
Mexico, Sánchez Magallanes (18.2967, -93.8545)	2022-01-15	13:10	-	-	-
	2022-01-16	07:30	-	-	-
Mexico, Isla Mujeres (21.2546,-86.7460)	2022-01-15	13:50	13:53	-	-
	2022-01-16	06:50	06:50	-	-
Mexico, Puerto Morelos (20.8681,-86.8668)	2022-01-15	13:50	13:51	-	-
	2022-01-16	06:50	06:51	-	-
Costa Rica, Limón (9.9886,-83.0203)	2022-01-15	13:50	-	13:34	-16 min
	2022-01-16	06:48	-	06:56	8 min
Puerto Rico, Mona (18.09,-67.9383)	2022-01-15	15:24	15:29	-	-
	2022-01-16	05:00	05:13	-	-
Puerto Rico, Mayagüez (18.2176,-67.1588)	2022-01-15	15:30	15:34	15:26	-4 min
	2022-01-16	04:48	05:09	03:15	-93 min

[continued]

Country/Territory, Station (Lat, Lon)	Observed pressure spike date (YYYY-MM-DD)	Observed pressure spike arrival (UTC)	Modeled pressure spike arrival (UTC)	Observed tsunami arrival (UTC)	Difference in arrival times (sea level - pressure spike)
Puerto Rico, Arecibo (18.4805,-66.7024)	2022-01-15	15:36	15:37	15:42	6 min
	2022-01-16	04:42	05:06	02:54	-108 min
Puerto Rico, San Juan (18.4617,-66.1167)	2022-01-15	15:36	15:40	15:39	3 min
	2022-01-16	04:42	05:03	03:22	-80 min
Puerto Rico, Culebra (18.3008,-65.3028)	2022-01-15	15:42	15:44	16:00	18 min
	2022-01-16	04:36	04:58	03:48	-48 min
Puerto Rico, Vieques (18.0939,-65.4714)	2022-01-15	15:42	15:43	15:35	-7 min
	2022-01-16	04:36	05:00	03:10	-86 min
USVI, Charlotte Amalie, St. T (18.335, -64.920)	2022-01-15	15:42	15:46	16:06	24 min
	2022-01-16	04:30	04:56	05:30	60min
USVI, Limetree, St. C (17.6947,-64.7538)	2022-01-15	15:36	15:46	15:54	18 min
	2022-01-16	04:30	04:56	04:30	0 min
USVI, Lameshur, St. J (18.3182,-64.7242)	2022-01-15	15:42	15:47	15:41	-1 min
	2022-01-16	04:30	04:55	05:48	78 min
USVI, Christiansted, St. C (17.74666,-64.69833)	2022-01-15	15:42	15:47	15:40	-2 min
	2022-01-16	04:30	04:56	05:36	66 min
St. Vincent, Calliaqua (13.129912,-61.1955)	2022-01-15	16:06	15:59	-	-
	2022-01-16	04:30	04:44	-	-
Trinidad & Tobago, Galeota (10.1387333,-61.00195)	2022-01-15	16:06	-	-	-
	2022-01-16	04:30	-	05:44	74 min
Grenada, Prickly Bay (12.005392,-61.764828)	2022-01-15	16:06	15:54	17:11	65 min
	2022-01-16	-	04:49	-	-
Dominica, Portsmouth (15.5768,-61.4582)	2022-01-15	16:06	-	15:56	-10 min
	2022-01-16	04:30	-	-	-
St. Lucia, Ganter's Bay (14.016428, -60.997351)	2022-01-15	16:06	-	16:08	2 min
	2022-01-16	04:05	-	03:00	-65 min
St. Lucia, Dennery (13.9114,-60.8865)	2022-01-15	16:18	-	16:20	2 min
	2022-01-16	04:05	-	-	-
St. Lucia, Vieux Fort (13.7209,-60.9528)	2022-01-15	16:18	-	16:12	-6 min
	2022-01-16	04:05	-	04:50	45 min
Martinique, Le Robert (14.678, -60.9408)	2022-01-15	15:51	15:58	15:55	4 min
	2022-01-16	04:05	04:27	04:13	8 min
Martinique, LePrêcheur (14.80758, -61.226588)	2022-01-15	15:50	15:57	15:52	2 min
	2022-01-16	03:48	04:29	04:01	13 min
Martinique, Fort-de-France (14.6018, -61.0636)	2022-01-15	15:51	15:57	15:55	4 min
	2022-01-16	04:05	04:28	03:30	-35 min
Guadeloupe, Pointe à Pitre (16.224, -61.5314)	2022-01-15	15:50	15:57	15:49	-1 min
	2022-01-16	03:48	04:28	04:10	22 min
Guadeloupe, Deshaies (16.3054, -61.7959)	2022-01-15	15:50	15:56	15:51	1 min
	2022-01-16	03:48	04:30	04:08	20 min
Brazil, Belém (-1.44224,48.49633)	2022-01-15	-	-	-	-
	2022-01-16	21:00	-	13:51	16.85 hrs
Brazil, Fortaleza (-3.7166,-38.4667)	2022-01-15	17:00	-	23:50	6.83 hrs
	2022-01-16	-	-	-	-
Brazil, Imbituba (-28.2308,-48.6508)	2022-01-15	16:00	-	23:24	7.4 hrs
	2022-01-16	-	-	-	-

ATMOSPHERIC AND SEA LEVEL DISTURBANCES

The first spike in barometric pressure traveled the Caribbean from West to East (Figure 9), being recorded first in the Tuxpan, Veracruz, Mexico station at around 12:50 UTC and recorded last in the Vieux Fort, St. Lucia station at 16:18 UTC. The variations found between stations and territories could be due to the differences in the topography of the landscape surrounding the stations, or the directionality of the pressure wave relative to the location of the stations. For instance, the barometric stations in Brazil have only recorded a single spike in air pressure for some stations, while others (Salvador) did not record any disturbances in barometric pressure. However, due to the previously stated differences in sampling rates, such observations

are only considered estimates, and there was no observable tsunami signal in the data near the assumed pressure spike. The gaps in the record are suggested to be due to the possibility of the Andes Mountains locally dispersing the signal (Dourado et al., 2022). Another important factor influencing the speed, and therefore its arrival at a given station, of the pressure wave may be the wind (Sepúlveda et al., 2023). Regarding sea level disturbances, bathymetry could also influence how the signal is recorded (e.g. shallow waters around continental platforms as a source of amplification). Similarly, weather conditions also affected the tsunami signal record on the Caribbean coast of Mexico, as an active cold front generated significant noise that likely overwhelmed the tsunami signal, making it too difficult to identify an arrival.

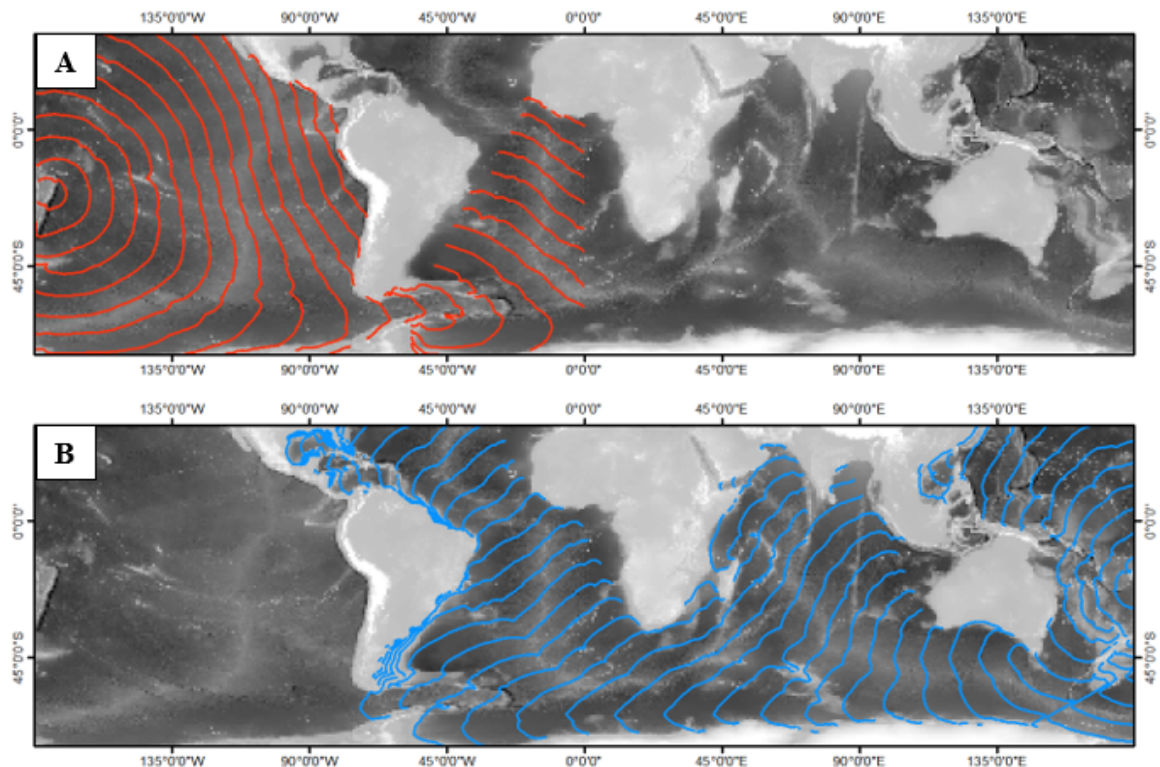


Figure 9. World map showing the dissipation of the tsunami waves from Hunga Tonga. (A) Waves traveling from West to East, which was the case for the 1st, 3rd, and 5th arrivals. (B) Waves traveling from East to West, which was the case for the 2nd, 4th, and 6th arrivals. Note how the travel time from the second turn-around (East to West) is longer and transverse more sea, which could be a possible explanation for the peculiarities observed in the data of the second pressure spike and tsunami arrival.

The second pressure wave traveled from East to West (Figure 9), as it was first recorded in the Guadeloupe stations and Le Prêcheur, Martinique at 03:48 UTC, closely followed by the Fort-de-France, Martinique station at 04:05 UTC, and last recorded in the Tuxpan, Veracruz, Mexico station at 08:00 UTC. This pressure wave had distinct peculiarities, most notably in the observations from the Puerto Rico stations. It was the only outlier with a delay from the tsunami signal of approximately 80 to 108 minutes, indicating that the two signals are no longer concordant. The fact that this was most distinguished in the Puerto Rico stations could indicate that a different mechanism or source influenced the pressure wave arrival.

The frequency spectrums were also much more complicated, showing multiple peaks (Figure 10). The observations from Puerto Rico and the USVI show some variations for the second pressure wave. Regarding the USVI, the differences in arrival times from the second pressure wave to the tsunami ranged from 60 minutes to 78 minutes, while in Puerto Rico, the differences in arrival times ranged from -48 to -108 minutes (with the tsunami arriving before the spike in barometric pressure). Similarly, the observations concerning arrival times from the French Antilles and the rest of the Lesser Antilles stations included in this study varied significantly. Even though these islands are near each other, this could also be due to differences in sensors, bathymetry, and topography.

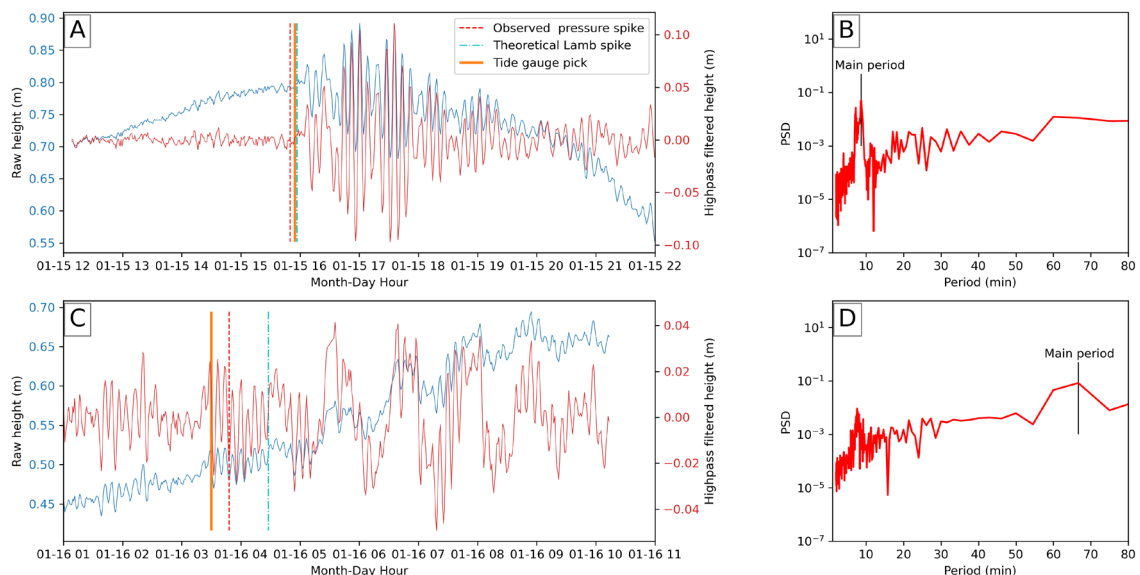


Figure 10. Sea level data at the Fort-de-France tide gauge station, ffr, showing the arrival of the two first tsunami waves and the pressure spikes. (A) Sea level data from 2022-01-15 12:00 to 22:00. (B) Power Spectral Density (PSD) of the signal in (A) vs the period. The main period is 8.7 minutes. (C) Sea level data from 2022-01-16 01:00 to 11:00. (D) PSD of the signal in (C) vs the period. The main period is 66.7 minutes. In (A) and (C) raw data are in blue and in red, data are filtered with a highpass filter ($1.7 \cdot 10^{-4}$ Hz to remove signal with a period greater than 100 min).

DISCUSSION

Observations indicate the air pressure and Lamb wave-generated tsunami are relatively coincident, with a difference of zero to 24 minutes in Puerto Rico, the USVI, Costa Rica and the French Lesser Antilles, excluding the second pressure wave. The second pressure spike had significantly higher differences in arrival times with the tsunami

wave, with some exceptions in Limón, Costa Rica; Limetree, St. Croix and Le Robert and Le Prêcheur in Martinique (Table 1). The observations from the other stations used in this study vary significantly. For instance, the Costa Rica station showed differences in arrival times ranging between -16 min for the first wave and eight min for the second wave, indicating that for the first arrival, the tsunami wave preceded the barometric pressure

wave. However, the barometric pressure was measured from an inland meteorological station of CIGEFI 112 km from the tide gauge as there was no co-located barometer station available. Similarly, a lot of the stations in Puerto Rico also recorded the tsunami wave arrival before the barometric pressure spike for either the first or second waves, along with stations in Lameshur, St. Johns; Christiansted, St. Croix; Portsmouth, Dominica; Ganter's Bay and Vieux Fort, St. Lucia; Pointe à Pitre, Guadeloupe and Fort-de-France, Martinique. In some instances, both the first and second tsunami waves preceded the pressure spike in the case of Mayagüez and Vieques. For Brazil, the differences in arrival times for all stations range in the magnitudes of hours, from 6.83 to 16.85 hours, which contrasts considerably with the records from the rest of the Caribbean stations. The vast differences in arrival times may stem from the varying bathymetric profiles along the Brazilian coast. In the Belém region, a wider continental shelf likely reduces wave speed more substantially upon entering shallower waters. In contrast, near Salvador, where the continental shelf is narrower, this deceleration effect is less pronounced. Thus, as waves encounter shallow waters after traveling at higher speeds across deep ocean waters, their arrival times differ depending on shelf width and depth variations, unlike the atmospheric pressure wave that travels at a constant speed across the entire path. This means that the arrival of the first crest of each wave was not the largest, and instead, the largest waves were often observed after the arrival of the leading wave, regardless of them traveling at the usual shallow-water wave velocity of $c = \sqrt{gh}$ (Carvajal et al., 2022). This could be a possible indication that the pressure wave is creating another signal of its own, although the specific meaning of this character change remains unclear. The resulting plots show there is a character change in the sea level once the pressure wave arrives at any given station in Puerto Rico, the USVI, and Martinique resulting in sea wave amplitudes of four to 15 centimeters, a lot larger than the background (Figure 11). The highest amplitudes did not correspond to the first arrival. Note that larger tsunami amplitudes were observed

when the atmospheric pressure wave was coming from the sea, rather than when the atmospheric wave came from land (Figure S2). This behavior was also observed in the atmospheric pressure-triggered tsunami caused by the Krakatoa eruption of 1883 (Ewing and Press, 1955; Harkrider and Press, 1967). Other studies have also suggested in ocean basins with both shallow and deep seas, such as the Caribbean and the Mediterranean, tsunamis are believed to be amplified in deep-water locations before propagating as amplified waves to shallow-water coastal areas (Omira et al., 2022). These authors also suggested the second tsunami was generated by the interaction of resonant ocean-gravity waves with acoustic-gravity waves, leading to the transfer of energy between air and water. This phenomenon occurs only in deep oceans when the velocity of the acoustic-gravity wave matches the velocity of long waves in the deep ocean (Proudman resonance causes wave amplification).

The second pressure wave stands out the most for its peculiarities, such as a significant time delay between the tsunami and the pressure wave arrivals, particularly in the Puerto Rico stations and, to some extent, in Vieux Fort and Ganter's Bay, St. Lucia, and the USVI stations. In addition, the French Antilles stations also recorded a more significant difference in arrival times for the second wave, although ranging from eight to -35 minutes, considerably less than the other stations in the Caribbean. This wave was anticipated to come from East to West across the region. However, given that later pressure waves from the same direction do not show such behavior, this could indicate another source must be present during the second wave. Similarly, the second pressure wave appears to last a lot longer when compared to the others, given that there is visible interference between the second and third pressure wave arrivals in the water level data plots for the Puerto Rico stations. This observation could indicate that as the first wave envelops the Earth, the second wave encounters and interacts with it, causing the visible interferences in the water level plots. Such interferences also correlate with what has been discussed more in-depth by previous studies of these effects in other locations (Zhang et al., 2022; Devlin et al., 2023).

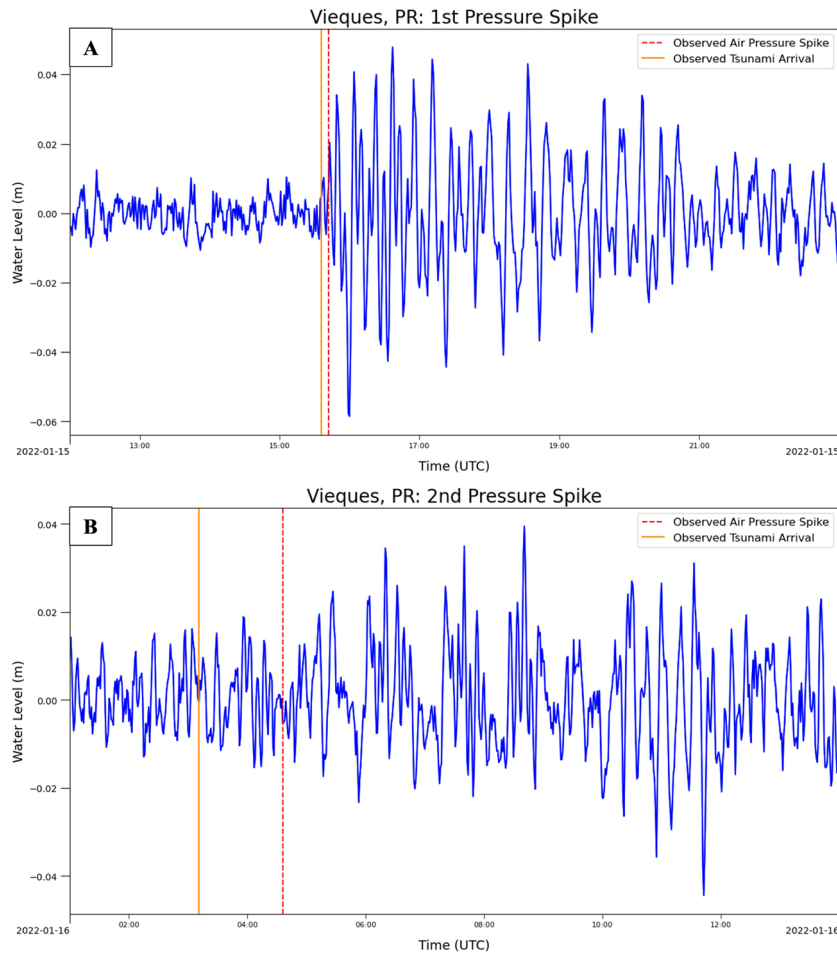


Figure 11. Filtered sea level plots from Vieques, Puerto Rico, showing the character change in sea level amplitudes (within the four to six cm range) after the arrival of the first pressure spike (A) and the second pressure spike (B). The time span between the first and second tsunami arrivals for this station was around 12.4 hours. Red dashed lines mark the arrival of the barometric pressure spike and the solid orange lines mark the arrival of the tsunami. In this case, the tsunami preceded the arrival of the pressure spike.

TSUNAMI PREPAREDNESS AND RESPONSE

Understanding the mechanisms behind this type of event and volcanic tsunamis has important implications for the Caribbean and adjacent regions. The population density that lives near the coast is alarming in terms of tsunami hazards and demonstrates the need for proper tsunami preparedness and awareness. This is especially highlighted by the fact that the Caribbean has 21 active volcanoes near the shore that could cause the same incident and violent eruption as Hunga Tonga (Venzke, 2013). Because of this, programs such as the UNESCO/IOC Tsunami Ready and the CARIBE WAVE

exercise (Soto et al., 2022) are critical in the formation of resilient communities and, therefore, in the reduction of tsunami risk caused by these hazards. The programs aim to prepare vulnerable communities for the event of a tsunami to mitigate the risk and reduce the loss of life and property. Moreover, workshops endorsing the gathering of subject matter experts can be extremely effective in risk management and beneficial for the overall community. Such gathering can be key in the identification of tsunami sources for the formulation of risk assessments focused on preparedness, mitigation, response, and recovery (IOC-UNESCO, 2020). In turn, this study reinforces the importance

of tsunami preparedness and accessible sea level data, as these could be invaluable in the hazard management of Tonga islands and other regions that suffered from this volcanic tsunami and could be impacted by future tsunamis.

CHALLENGES ENCOUNTERED DURING THE STUDY AND AREAS OF IMPROVEMENT

This study highlights the need for the standardization of what depicts the definition of tsunami arrival times in the tsunami science community. During the process of compiling and processing the data, various challenges were encountered. In part, the process of data acquisition was complicated due to the lack of a curated global data repository for sea level. For instance, the IOC states its objective is to provide information on the status of real-time sea level stations and offers the raw data stream from each station. This implies, as stated in their disclaimer, the data provided has not undergone any quality control and the sampling frequency as well as the data transmission varies per station (VLIZ, 2022). Unlike earthquake data, tsunami and sea level data can only be acquired via specific resources depending on the local government. Because of this, finding data with the same sampling rate across the different stations from the region was also a challenge, meaning that standardization of the data format itself is needed. On the other hand, the lack of standardization or definition of what marks the arrival of a tsunami in sea level data leads to the employment of multiple methods or definitions being used in each study. Different methods in picking arrival times have increased errors and uncertainties in this study, which affects the science reliability. For instance, picking a tsunami arrival time based on the highest amplitude in the sea level data will lead to a considerably different outcome than picking an arrival time based on the first deviation in the sea level data. Such differences could range from 10 to 20 minutes or more, depending on the sampling rate of the instrumentation as well as the interpretation of the scientist picking the arrival, affecting the accuracy of the tsunami arrival time at a given station. Determining a standardized definition for the arrival of a tsunami signal could be invaluable in the future of tsunami hazard

science, paving the way for more reproducible and reliable science.

In addition, the volcanic tsunami generated by the Krakatau eruption of 2018 raised awareness of fundamental gaps in the tsunami early warning system that has been widely implemented and designed for earthquake-induced tsunamis (Clouard et al., 2024; IOC-UNESCO, 2020). The rarity and tremendous hazard potential of the HTHH 2022 eruption serve as a reminder of such gaps as it also displayed the need for reinforced tsunami early warning systems at different scales, from local to regional systems (von Hillebrandt-Andrade et al., 2023). For instance, the authorities of Costa Rica issued a warning of the tsunami that was generated by HTHH one to two hours before the arrival. Nonetheless, the warning did not reach all citizens, and some on remote beaches found out only when it was already visible on the coast (Chacón-Barrantes et al., 2023). Although no one was injured, this highlights the gaps of the current early warning system, which has been developed based on earthquake-generated tsunamis, which are the most common source of tsunamis. However, volcanic tsunamis differ from tsunamis generated by earthquakes in terms of precursors, generation mechanism, propagation, and impact (Paris, 2015), giving them the potential to be deadly regardless of occurring less commonly. The immense lack of response procedures for volcanic-generated tsunamis poses an even greater threat to vulnerable populations around the world, particularly at a local scale around active volcanoes, which could produce near-field volcanic tsunamis.

CONCLUSION

The January 15th, 2022, eruption of the HTHH volcano and related tsunamis were a once in a century phenomenon, and as such, there is still much to debate on how to approach all recorded data for processing and analysis. As such, cooperation between the CARIBE-EWS experts in the form of regular meetings, discussions, and sharing of data was crucial for the development of this study. Without the contributions of each member, a report such as this one on the observations of the HTHH eruption

in the Caribbean and adjacent regions would not have been possible. Overall, about six barometric pressure spikes were observed throughout the Caribbean stations, spanning a period of about 90 hours. In the case of Puerto Rico, the French Antilles, and the USVI, the first pressure wave arrival was found to be nearly coincident with the tsunami's arrival. The observations from the USVI data varied considerably from those of Puerto Rico for the second pressure wave, with greater differences in arrival times and frequency content. Likewise, the observations from the French Antilles varied significantly from the rest of the Lesser Antilles stations in this study by having the most coincidental arrival times between the barometric pressure wave and the tsunami. However, all plots demonstrated that with the arrival of each pressure wave, there was a clear character change in the sea level data, making the wave amplitudes much larger, which was consistent with observations from other published studies. Observations also indicate that the surrounding topography of the barometric station could significantly influence the recording of pressure waves, as well as the bathymetry, and in some cases, the weather also had major impacts on the tsunami arrivals and amplitudes. Much is yet to be investigated as data from the rest of the Caribbean is organized and analyzed. Future work for this project should include a thorough process of data quality control, which were compiled from different repositories, including searching for means of standardizing the data format. Currently, there is no standardized method for identifying the first arrival of a barometric pressure wave or a tsunami signal. This study highlights the necessity to define what the first arrival should imply, as the lack of standardization could be problematic for future occurrences and investigations in tsunami science by increasing uncertainties and reducing the reproducibility of the scientific method. Therefore, by establishing a definition for tsunami arrival, future investigations of similar events may become more reliable and efficient in the characterization of tsunami signals. This study also emphasizes the need for developing tsunami early warning systems and response protocols that consider volcanic sources. Increasing

knowledge of the different tsunami generation mechanisms and sources, as well as having sea level data widely available, has a tremendous potential to empower communities that are particularly vulnerable to this threat. Motivating at-risk communities to be a part of emergency response protocols, such as the Tsunami Ready program and the CARIBE WAVE exercise, are very effective means for reducing tsunami risk. Because of the tsunami preparedness protocols that are in place for Tonga, such as having regular evacuation drills, the death toll was kept to a minimum. This proves the invaluable potential that those programs possess and demonstrates why tsunami awareness and preparedness should be a top priority for coastal communities.

DATA AVAILABILITY STATEMENT

The data that supports the results reported in the study can be accessed in publicly archived datasets at the links provided in the Bibliography, primarily UNESCO-IOC Sea Level Monitoring Facility, CO-OPS/ NOAA NCEI, and NOAA Tides and Currents. Rede Maregráfica Permanente para Geodésia data are available at www.ibge.gov.br. National Sea Level Monitoring Service (Servicio Mareográfico Nacional) data are available free of charge via request on the portal www.mareografico.unam.mx.

SUPPLEMENTARY MATERIAL

Figure S1: 2022 HTHH Volcano Tsunami. Air-Ocean Coupled Model can be found at <https://doi.org/10.5281/zenodo.13134977>. Figure S2: All 6 Barometric Pressure Spikes from HTHH 2022, as Seen in Mayagüez, Puerto Rico, can be found at <https://doi.org/10.5281/zenodo.13137431>.

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AUTHOR CONTRIBUTIONS

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E.A.V.: Conceptualization; Methodology; Software; Visualization; Formal Analysis; Validation.

C.v.H.A.: Supervision; Resources; Project Administration; Writing – review & editing.

R.A.W.: Data Curation; Formal Analysis; Validation.

V.C.: Data Curation; Formal Analysis; Validation; Writing – review & editing.

S.CH.B.: Data Curation; Formal Analysis; Validation; Writing – review & editing.

F.D.: Data Curation; Formal Analysis; Validation.

O.G.R.: Data Curation; Formal Analysis; Validation.

E.P.J.: Data Curation; Formal Analysis; Validation; Writing – review & editing.

R.P.: Formal Analysis; Validation; Writing – review & editing.

CONFLICTS OF INTEREST

The authors have no personal, commercial, political, academic, financial, or other interests that could influence the preparation or evaluation of the manuscript.

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