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RESEARCH ARTICLE

Impact of the tsunami caused by the Hunga Tonga–Hunga Ha'apai eruption in Costa Rica on 15 January 2022

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Abstract
Hunga Tonga–Hunga Ha'apai had a large eruption (VEI 5–6) on 15 January 2022, which caused a tsunami recorded in all ocean basins. Costa Rica has made many advances in tsunami preparation over the past 9 years since the creation of SINAMOT (*Sistema Nacional de Monitoreo de Tsunamis*, National Tsunami Monitoring System), both on watch and warning protocols and on community preparedness. For the Hunga Tonga–Hunga Ha'apai event, the government declared a low-threat warning, suspending all in-water activities, even though the country did not receive any official warning from PTWC (Pacific Tsunami Warning Center) due to the lack of procedures for tsunamis generated by volcanoes. The tsunami was observed at 24 locations on both the Pacific and Caribbean coasts of Costa Rica, becoming the second most recorded tsunami in the country, after the 1991 Limon tsunami along the Caribbean coast. At 22 of those locations along the continental Pacific coast, observations were made by eyewitnesses, including one collocated with the sea level station at Quepos, which registered the tsunami. At Cocos Island (~ 500 km southwest of the continental Costa Rica, in the Pacific Ocean), several eyewitnesses reported the tsunami at two locations, and it was recorded at the sea level station. The tsunami was also recorded at the sea level station on the Caribbean coast. The tsunami effects reported were a combination of sea level fluctuations, strong currents, and coastal erosion, proving that the response actions were adequate for the size of the tsunami. Tsunami preparedness and the largest waves arriving during a dry season Saturday afternoon allowed the large number of eyewitness reports. This event then increased tsunami awareness in the country and tested protocols and procedures. Still, many people along the coast were not informed of the tsunami during the alert due to their remote location, the short notice of the warning, and a lack of procedures for some communities. There is thus still much work to do, particularly about warning dissemination, a direction in which communities should take an active role.

Keywords Tsunami · Hunga Tonga–Hunga Ha'apai · Shock wave · Tsunami warning · Tsunami response · Tsunamis generated by volcanoes

Introduction

Costa Rica has 273 coastal communities on the Pacific coast distributed between 685 beaches along 1016 km of coastline (Arozarena Llopis et al. 2015). The country has experienced 42 tsunamis since 1746 (Chacón-Barrantes et al. 2021b; NOAA/NCEI 2022). Two of the most significant tsunamis were in 1991 on the south Caribbean coast after the Limón earthquake (Camacho 1993; Nishenko et al. 2021) and in 1992 on the north Pacific coast after the Nicaragua earthquake (Satake et al. 1993). These two events had run-ups of less than 5 m and caused flooding along the south Caribbean and north Pacific coasts respectively, with the 1991 tsunami causing at least three deaths (Chacón-Barrantes et al. 2021b). Although a first review of historical tsunamis in Costa Rica was carried out in the 1990s as part of a joint Central America and Norway effort (Fernández-Arce et al. 1993, 2000; Molina 1997; Fernández-Arce and Alvarado-Delgado 2005), no tsunami hazard assessments were performed until 2016 (Chacón-Barrantes and Arozarena Llopis 2021).

Costa Rican coasts were traditionally sparsely populated, as the government was not interested in promoting tourism on the coasts until the 1980s and the 1990s (Arrieta Murillo

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and Rivera Hernández 2009). This contributed to most people not considering tsunamis as a threat and sometimes not even considering tsunamis as a possibility, even after the 1990s events.

As a result, the *Sistema Nacional de Monitoreo de Tsunamis* (SINAMOT www.sinamot.una.ac.cr), a National Tsunami Monitoring System for Costa Rica was established in 2014. SINAMOT is a research and outreach program for tsunamis based at the National University (Heredia, Costa Rica) (Chacón-Barrantes 2015). In late 2015, SINAMOT began a project with the National Commission for Risk Prevention and Emergency Response (*Comisión Nacional de Prevención de Riesgos y Atención de Emergencias,* CNE), to create tsunami evacuation maps for coastal communities in Costa Rica (Rivera et al. 2016; Chacón-Barrantes et al. 2021a). The first stage of the project involved working with communities along the north and central Pacific coasts, a task which was completed in 2018. The second stage of the project between 2019 and 2022 then involved working with communities along the southern Pacific and Caribbean coasts. Despite delays related to the COVID-19 pandemic, more than 60 coastal communities along both coasts now have tsunami evacuation maps as a result of this project.

By January 2022, 11 of these communities also had tsunami preparedness and response plans, as based on the evacuation maps; and tsunami evacuation route signage has been installed for 13 communities, an effort funded by CNE, the International Migration Organization (IMO), and the United States Agency for International Development (USAID). As a result, by January 2022, Costa Rica had five communities recognized as UNESCO/IOC Tsunami Ready by the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (ITIC 2022a). By March 2023, five more communities had been recognized as UNESCO/IOC Tsunami Ready, and several more are in the process of fulfilling the requirements of the recognition program. Prior to 2022, these requirements were defined by 10 mitigation, preparedness, and response actions as stated by the Pilot Tsunami Ready Recognition Program of the Intergovernmental Coordination Group of the Pacific Tsunami Warning System (ICG/PTWS). In early 2022, a set of 12 unified UNESCO/IOC Tsunami Ready guidelines on assessment, preparedness, and response were approved for recognition at all the four Tsunami Warning Systems worldwide (UNESCO/IOC 2022a).

SINAMOT has also been the National Tsunami Warning Centre for Costa Rica since 2015 (Chacón-Barrantes 2015; UNESCO-IOC 2016; Chacón-Barrantes et al. 2021a). Globally, tsunami warning protocols and procedures had been generally designed for earthquake-generated tsunamis, as such events represent about 86% of tsunamis generated worldwide (NOAA/NCEI 2022) and almost all far-field tsunamis. Therefore, the far-field tsunami caused by the eruption of Hunga Tonga–Hunga Ha'apai on 15 January 2022 represented a challenge for the tsunami warning systems involved both at regional and national levels.

To help fill this knowledge gap, we thus provide a summary of the warning and response actions taken by Costa Rica and the observations reported for the tsunami caused by the Hunga Tonga–Hunga Ha'apai eruption, as it arrived along the Pacific and Caribbean coastlines (Fig. 1).

Warning and response actions

The explosive eruption of Hunga Tonga–Hunga Ha'apai occurred at 22:14 on 14 January 2022 Costa Rican time, which was 04:14 UTC on 15 January (ITIC 2022b). Hereafter, all times are given in local Costa Rican time, which is – 6:00 UTC. Times in UTC will be given in parentheses in some cases.

The Pacific Tsunami Warning Centre (PTWC) "monitors seismic and sea level activity and issues timely tsunami threat information" to Member States of the Pacific Tsunami Warning System (ICG/PTWS) and of the Tsunami and Other Coastal Hazards Warning System for the Caribbean and Adjacent Regions (ICG/CARIBE-EWS) (UNESCO-IOC 2016; Chacón-Barrantes et al. 2021a). PTWC estimated that a tsunami had been generated at 22:27 (Fig. 2) and issued their first message manually at 00:23 on 15 January (06:23 UTC) to all countries bordering the Pacific, including Costa Rica.

For unknown reasons, all countries of Central America, including Costa Rica, and many other countries did not receive the first six messages from PTWC. At SINAMOT, we learned about the tsunami at about 09:30 via a Latin-American tsunami researchers WhatsApp group, when colleagues from Chile shared the arrival of the tsunami at their Easter Island tide gauge.

At 11:16, SINAMOT realized that PTWC was issuing messages, when a colleague from the USA forwarded the PTWC Message #5 to an email list that includes SINAMOT. Following this, SINAMOT consulted with Central American colleagues and notified PTWC that countries in the region were not receiving the messages. At 13:30, all Caribbean countries, including those of Central America, received the PTWC Message #1 for the Caribbean, as the tsunami was recorded at several sea level stations in the Caribbean. Then, at 14:21, we received Message #7 for the Pacific.

At both regional and national levels, the threat analysis was hindered by a lack of tools to perform a tsunami amplitude and arrival time forecast for non-seismic tsunamis. Despite this, at SINAMOT, we were able to estimate that this tsunami was going to cause strong currents and minor sea level fluctuations, but no flooding. This fitted the criteria for release of a low-threat statement. Our assessment was based

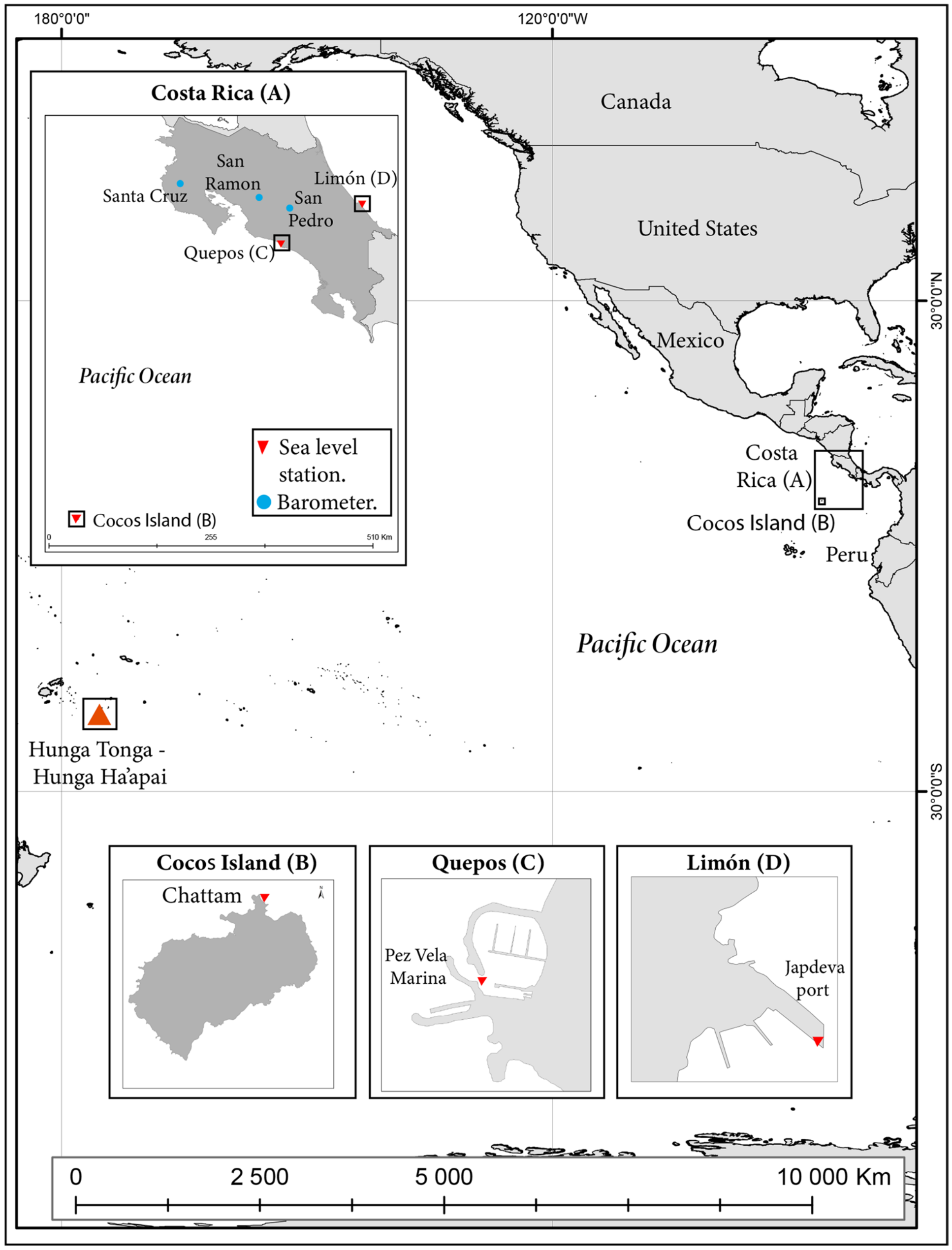

Fig. 1 Localization of the Hunga Tonga–Hunga Ha'apai volcano relative to Costa Rica. (A) Localization of Costa Rican sea level stations (red triangles) and barometers (blue dots). More details on the sea level gauges in insets: (B) Cocos Island, (C) Quepos, and (D) Limón

on the real-time sea level records around the Pacific basin and results from tsunami hazard studies performed by SINAMOT previously (Chacón-Barrantes and Arozarena Llopis 2021). Therefore, at 09:54, SINAMOT issued a first report indicating "low threat," the lowest of the three threat levels established by SINAMOT's Standard Operating Procedures (SOPs) and recommending the cessation of any in-water activity.

SINAMOT then used tsunami travel time models for earthquake-generated tsunamis to estimate the likely tsunami arrival time, resulting in 12:20 for Cocos Island and 12:53 for the mainland, using 22:27 (Jan. 14) as the origin time. Based on this report, CNE activated local and municipal emergency committees along the Pacific coast. In communities not having local emergency committees, the municipal emergency committees run warning dissemination and were thus contacted.

First responders such as policemen, coastguards, lifeguards, and Red Cross oversaw alerting of people on many beaches. In almost all places, people got out of the water, but stayed on the beach. This contributed to the tsunami being observed in many locations. Nevertheless, many people reported have been at the beach on Saturday afternoon and not receiving any warning. Some of these witnesses observed the tsunami and reported it.

At 16:05, SINAMOT issued report #6 indicating the threat had passed, as sea level variations reported by

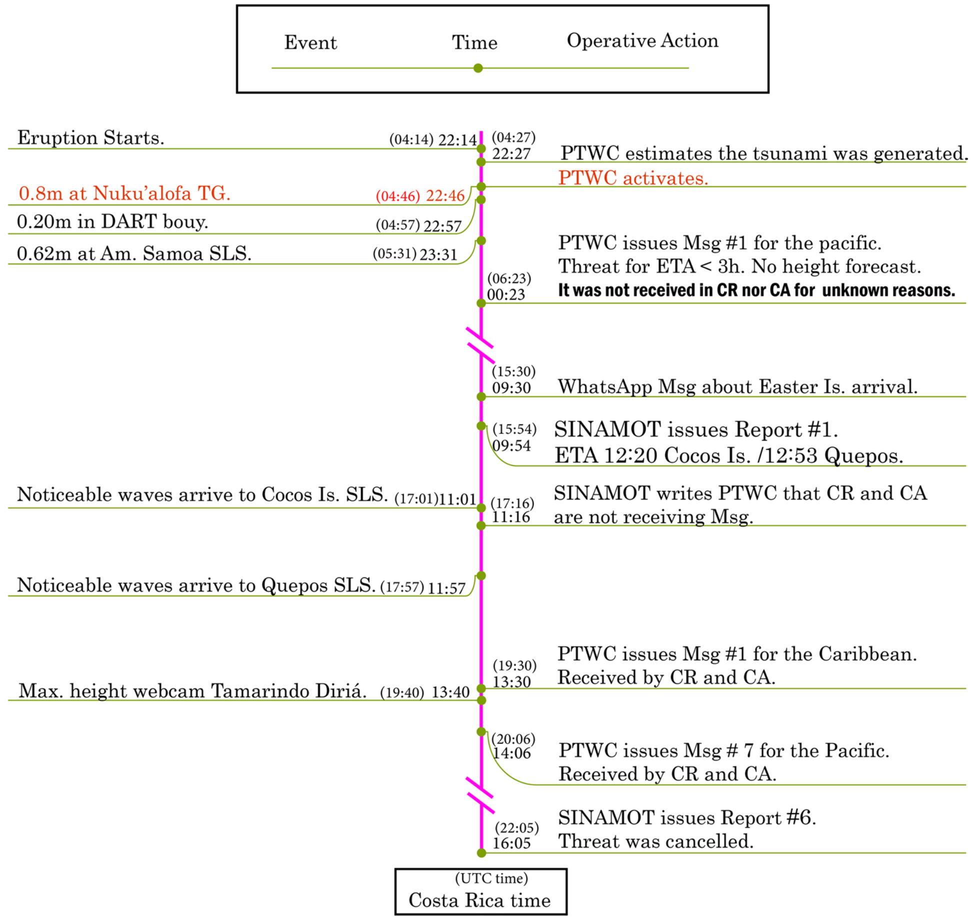

Fig. 2 Timeline of the event (left) and the response actions (right) in CR local time. UTC times in parenthesis

witnesses at beaches had stopped by that time. This report stated that some strong currents might remain in marinas, ports, and bays and could continue for several more hours. However, considering that the currents caused some trouble at Quepos marina (Fig. 1) around that time and later, we now consider that the warning should have remained active for ships and swimmers at specific locations such as Quepos, as well as Potrero, Tamarindo, and Cocos Island, during the rest of the day and even for the day after.

Methods

The generation process of this tsunami was complex, as it did not correspond to a unique nor static source. Three tsunami generation mechanisms appear to have been related to this volcanic eruption (Kubota et al. 2022; Lynett et al. 2022):

1. Coupling of atmospheric Lamb waves with the ocean to create pressure-generated tsunamis which propagated coupled with the shock waves across the world's oceans, hereafter named meteotsunami
2. Explosion and pyroclastic density currents that caused the largest tsunami waves but with localized effects
3. Proudmann resonance of the meteotsunami when reaching the Pacific trenches, which then propagated freely over the Pacific

The tsunami waves caused by the explosion and pyroclastic density currents (generation mechanism #2) were very likely not recorded in Costa Rica as their energy quickly dispersed, due to their wavelength, reaching only coastlines proximal to the volcano. The third mechanism, however, created tsunami waves at each Pacific Trench. These then overlapped with each other, making it impossible to forecast the arrival times for these waves; we refer to these waves as a single freely propagating tsunami.

The meteotsunami (generation mechanism #1) was associated with the smallest wave heights but arrived first, as it traveled together with the shock wave at an average speed of 280–320 m/s independent of ocean depth (Kubota et al. 2022). Therefore, the first tsunami arrivals were recorded by sea level stations at many locations in the Pacific and Atlantic Oceans, including the Caribbean Sea, at about the same time as the peak of the shock wave recorded by meteorological stations collocated with the sea level stations

(Ortiz-Huerta and Ortiz 2022; Omira et al. 2022; Sostre-Cortes et al. 2022). For Pacific countries, the meteotsunami arrival time was thus up to several hours before the forecast, which were modeled using a seismic source and thus did not consider the shock wave. The velocity of tsunamis propagating freely over the ocean depends on the ocean depth, this propagation velocity is usually smaller than the velocity of the shock wave.

Costa Rica has three Sea Level Stations (SLS) at Cocos Island, Quepos and Limón (Fig. 1 and squares in Fig. 3). These stations perform a 1-min average of 3-s samples and transmit every 6 min. Cocos Island SLS is located at the foot of a cliff, Quepos SLS is located inside a Marina, and Limón SLS is located in a dock (see insets to Fig. 1). Unfortunately, there are no meteorological stations (MetS) collocated with the SLSs; thus, we needed to estimate the arrival time of the shock wave at the location of each SLS. The National Meteorological Institute of Costa Rica (*Instituto Meteorológico Nacional*, IMN) has several MetSs close to the SLSs, but they only record hourly averages; thus, the peak of the shock wave was not registered. The Geophysical Research Center (CIGEFI) at the University of Costa Rica (UCR) has four MetSs, two of which sample every half an hour and which were also not capable of registering the

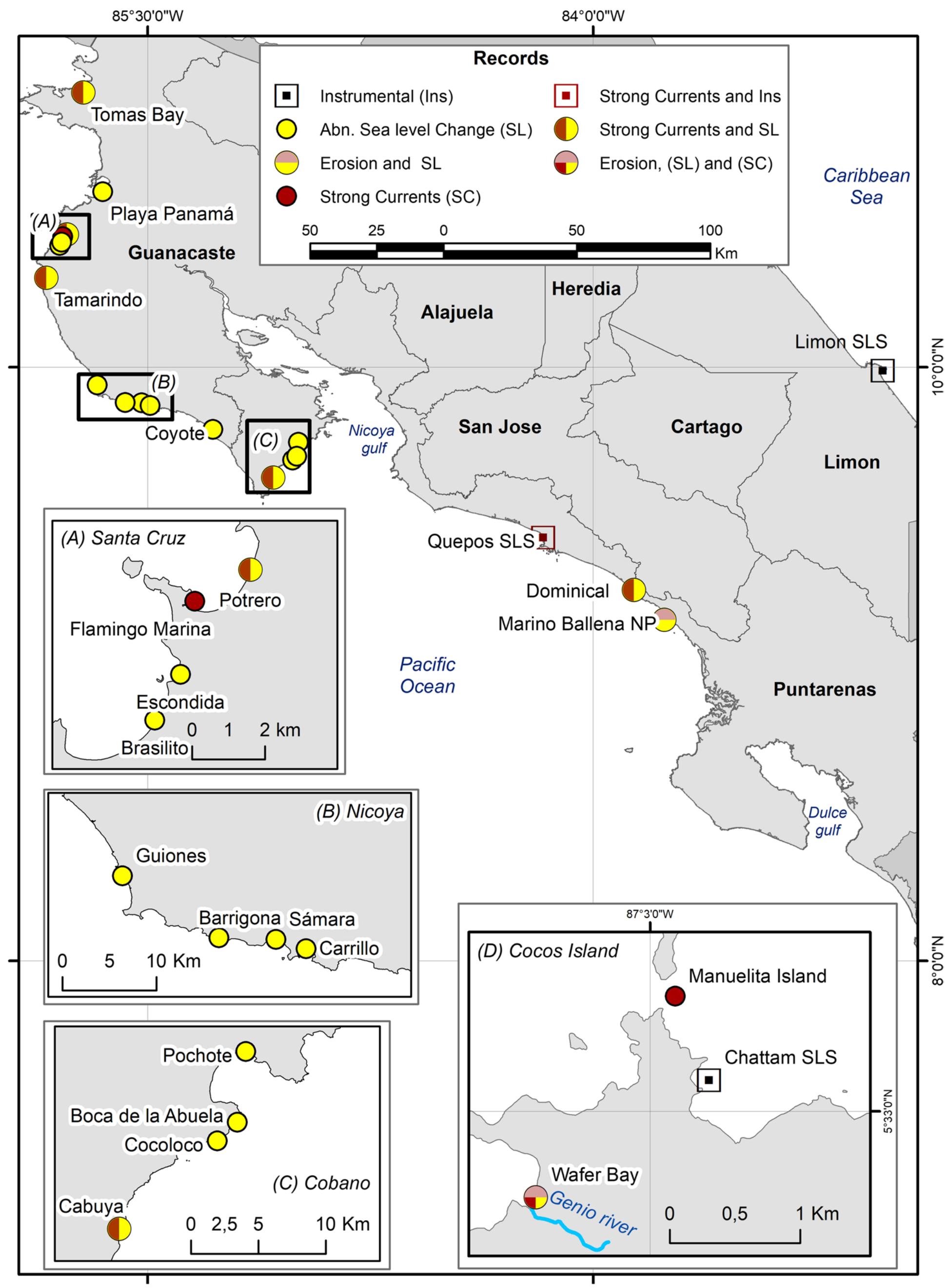

Fig. 3 Map showing the location of tsunami observations and records in Costa Rica and its effects. Squares indicate sea level station records, yellow circles indicate sea level fluctuations, dark red circles indicate strong currents, and pink circles indicate coastal erosion. Combined circles show combined effects according with the color code: circles divided horizontally indicate erosion and sea level changes, circles divided vertically indicate strong currents and sea level changes, and circles divided in three show the three effects combined

shock wave. However, the UCR MetS located at San Ramón records data every 5 min, and that located at the Geophysical Research Center building in San Pedro records data every minute (Fig. 1). The Climate System Observation Laboratory of the Physics School of UCR also has a high-resolution MetS at Santa Cruz (Guanacaste), which records data every second (Fig. 1).

The eruption started at 22:14 on 14 January, Costa Rican time. The peak of the first shock wave arrived in Santa Cruz at 07:40, in San Ramón at 07:45, and at San Pedro by 07:50 (Fig. S1, Supplementary Material). The distances between these three MetSs and the Hunga Tonga–Hunga Ha'apai volcano are 11,360; 11,470; and 11,510 km, respectively. Using these distances and travel time parameters, we calculated the velocity of the first shock wave as 334, 335, and 333 m/s, respectively. We used the median (334 m/s) and the distance between the volcano and each SLS to estimate the first shock wave arrival time at each sea level station.

The atmospheric shock wave traveled around the world several times. At the three Costa Rican MetSs, at least six shock waves were recorded in the days following the eruption (Fig. S1, Supplementary Material). However, the estimation of arrival times for the subsequent shock waves to the SLSs was not straightforward. We decided to use as reference the Santa Cruz meteorological station as it has the highest sampling rate. To estimate the arrival times for the second through the sixth shock waves at Cocos Island, Quepos, and Limón, we calculated the distances between the Santa Cruz meteorological station and each of the three SLSs (Table 2). We then used these distances with the velocity calculated for the first shock wave to estimate the travel time of the shock waves between the Santa Cruz meteorological station and the SLSs. Odd-numbered shock waves arrived from the west and even-numbered shock waves arrived from the east. Therefore, depending on the position of the SLS relative to the Santa Cruz meteorological station, we added or subtracted the travel time to the Santa Cruz meteorological station arrival time for each shock wave. These are approximations as the travel velocity for the shock wave is not constant, and the incidence angle is not perpendicular to the distance between stations, but the uncertainty is likely of the order of a few minutes.

Processing of the sea level data for the three SLSs first involved eliminating the tide. To do this, we applied a high-pass filter with a 2.5-h period (frequency = 1.1×10^{-4} Hz) (Figs. 4b, 5, 6b, 7, 8b, and 9 plus Figs. S1, S2, and S3 in the Supplementary Material). We then performed a spectral analysis using a Fourier discrete transform (DFT) to search for the tsunami frequencies (Fig. 10) and calculated spectrograms using the short-time Fourier transform (STFT) (Figs. 4a, 6a, and 8a). The arrival times of the freely propagating tsunami for Cocos Island and Quepos SLS were obtained from the spectrograms, as

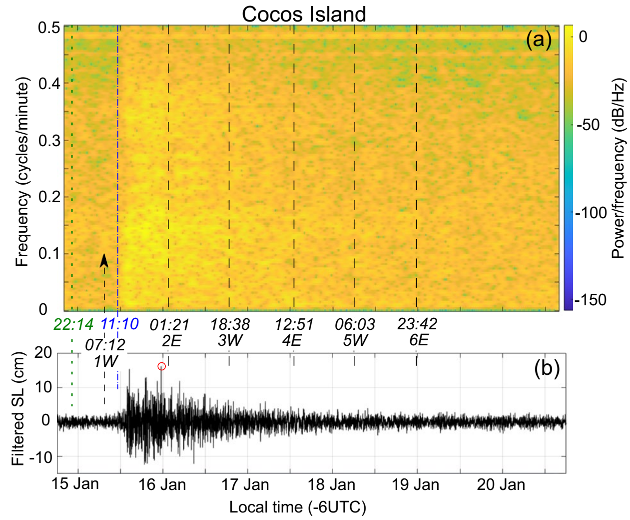

Fig. 4 Cocos Island. Upper panel: spectrogram of the filtered sea level record. Lower panel: filtered sea level record. The green dotted line shows the eruption time. Black dashed arrow and dashed lines show the estimated arrival time for the first six shock waves: (1) 15 Jan 07:12 from the west, (2) 16 Jan 01:21 from the east, (3) 16 Jan 18:38 from the west, (4) 17 Jan 12:51 from the east, (5) 18 Jan 06:03 from the west, and (6) 18 Jan 23:42 from the east. The blue dashed-dotted line shows the arrival time for the freely propagating tsunami obtained from the spectrogram: 11:10. The red circle shows the maximum tsunami amplitude of 16.2 cm on 15 Jan 23:25

this tsunami was larger (and thus more energetic) than the meteotsunami.

Results

The tsunami caused by the Hunga Tonga–Hunga Ha'apai volcano was the first tsunami to be recorded on both the Pacific and Caribbean coasts of Costa Rica, at two and one sea level stations, respectively. Also, it was the first tsunami to be recorded at the sea level station on the Caribbean coast since it was deployed in 1940 (Chacón-Barrantes and Gutiérrez-Echeverría 2017). In total, the tsunami was observed at 24 locations nationwide, as there were eyewitness reports at 22 locations on the Pacific coast (Fig. 3); one of those reports was collocated with the Quepos station (Fig. 1). It became the most observed tsunami in the Pacific coast of Costa Rica.

Regarding the sea level stations, we estimated that the first shock wave and the meteotsunami arrived at 07:12 on Cocos Island, 07:30 at Quepos, and 07:54 at Limón (Table 1). The time of the subsequent shock wave arrivals to each SLS is listed in Table 2.

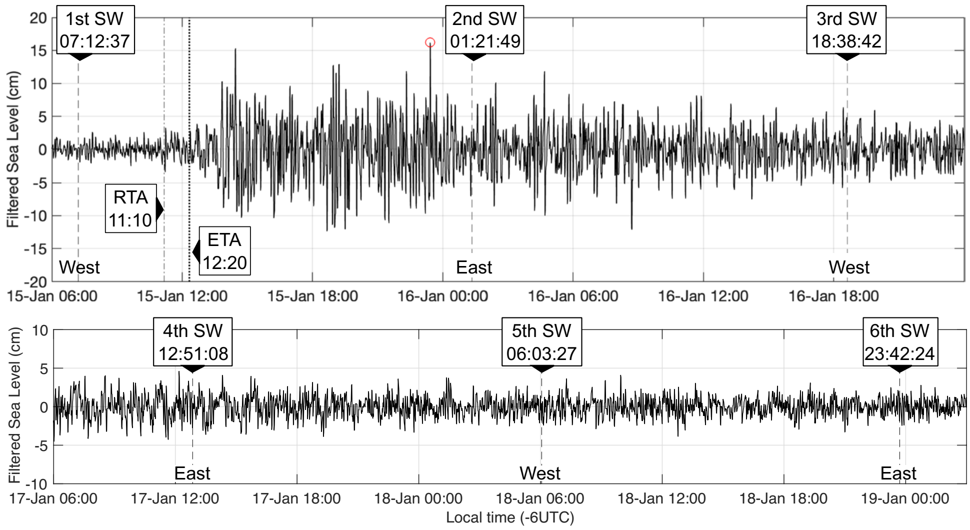

Fig. 5 Filtered sea level record at Cocos Island sea level station for 15 to 19 January. Dashed lines show the arrival time for the first six shock waves to the sea level station, calculated from arrival times to the Santa Cruz Meteorological Station. Odd-numbered shock waves propagated from west to east; even-numbered shock waves propagated from east to west. The dashed-dotted line shows the real arrival time (RTA) and the dotted line shows the estimated arrival time (ETA) of the freely propagating tsunami. The red circle shows the maximum tsunami amplitude of 16.2 cm on 15 Jan 23:25. The location of the sea level station is shown in Fig. 1

Pacific sea level stations

For the Cocos Island sea level records, we found a peak in power on 15 January 07:12, corresponding to a frequency of 0.1308 min^{-1} with a period of 7.7 min (dashed arrow at Fig. 4a). This time agrees with the estimated arrival time of the first shock wave (Table 1), and the frequency corresponds to one of the peaks in the spectral analysis (Fig. 10a). This first arrival was of the order of the background noise having an amplitude (peak to zero) of 0.8 cm, a corresponding wave height (peak-to-trough) of 0.98 cm and a period of 7.7 min (Table 2 and Fig. 5). The first waves that overcame the background noise started to arrive at around 11:10 with an amplitude of 3.3 cm, a wave height of 6.7 cm, and a period of 6 min (Table 2 and dashed-dotted line Fig. 5). This corresponds with an increase in power for frequencies below 0.4 min^{-1}, i.e., periods greater than 2.5 min, at that time in Fig. 4a, indicating the arrival of the freely propagating tsunami. It was not possible to see any changes in power per frequency at the estimated arrival time for shock waves two to six. The maximum tsunami amplitude at Cocos Island was 16.2 cm on 15 January at 23:25 and had a wave height of 23.2 cm and a period of 5 min (Table 2 and circle in Fig. 5).

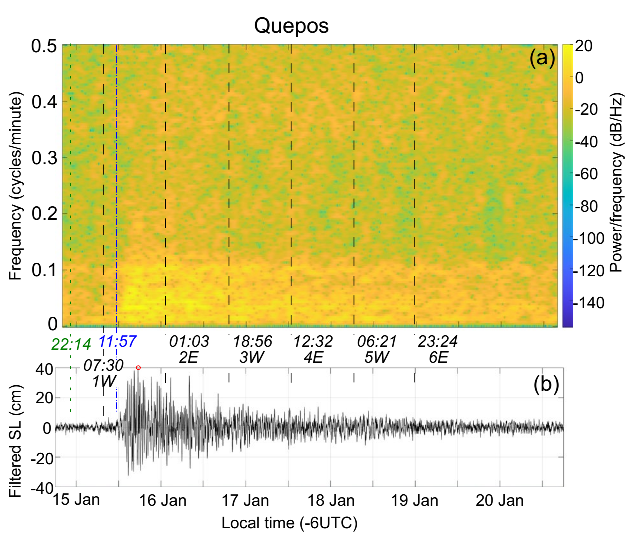

Fig. 6 Quepos. Upper panel: spectrogram of the filtered sea level record. Lower panel: filtered sea level record. The green dotted line shows the eruption time. Black dashed lines show the arrival time for the first six shock waves: (1) 15 Jan 07:30 from the west, (2) 16 Jan 01:03 from the east, (3) 16 Jan 18:56 from the west, (4) 17 Jan 12:32 from the east, (5) 18 Jan 06:21 from the west, and (6) 18 Jan 23:24 from the east. The blue dashed-dotted line shows the arrival time for the freely propagating tsunami obtained from the spectrogram: 11:57. The red circle shows the maximum tsunami amplitude of 39.6 cm on 15 Jan 17:27

In the Quepos spectrogram, there was an increase in power at frequencies smaller than 0.1 min^{-1} (periods greater than 10 min) on 15 January 07:30. This corresponds to the estimated arrival time of the shock wave and the meteotsunami coupled to it (first dashed line in Fig. 6a and Table 1). Nevertheless, we were not able to distinguish a wave arriving at that time in the filtered sea level data (Fig. 7). A 20-min period, 3.9 cm amplitude, and 5.5-cm-high wave arrived at Quepos at 08:00. This could be related to the meteotsunami (first dashed line Fig. 7). A stronger increase in power for frequencies

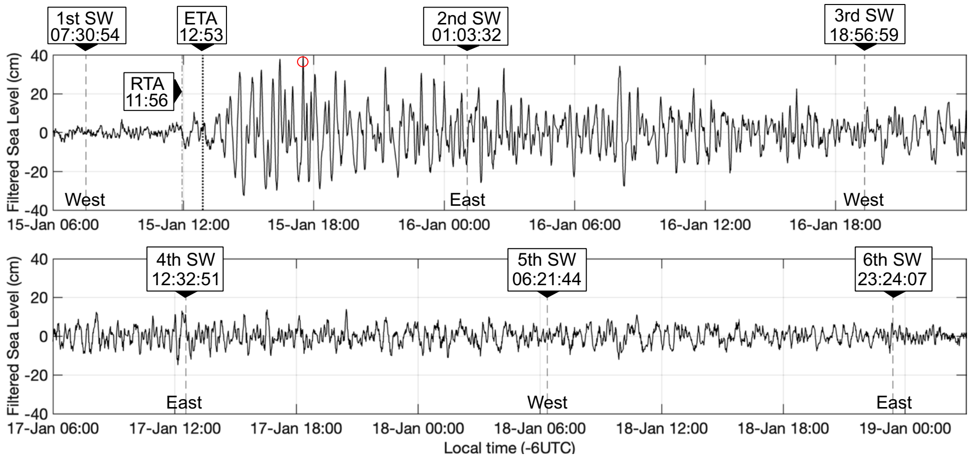

Fig. 7 Filtered sea level record at Quepos sea level station for 15 to 19 January. Dashed lines show the estimated arrival time for the first six shock waves to the gauge location, calculated from arrival times to the Santa Cruz Meteorological Station. Odd-numbered shock waves propagated from west to east; even-numbered shock waves propagated from east to west. The dashed-dotted line shows the real arrival time (RTA) and the dotted line shows the estimated arrival time (ETA) of the freely propagating tsunami. The red circle shows the maximum tsunami amplitude of 39.6 cm on 15 Jan 17:27. The location of the sea level station is shown in Fig. 1

below 0.2 min^{-1} (periods higher than 5 min) occurred at 11:57, starting with frequencies of about 0.02 min^{-1} (50-min period) (dashed-dotted line in Fig. 6a), indicating the arrival of the freely propagating tsunami (dashed-dotted line in Fig. 7). It was not possible to see any changes in power per frequency at the estimated arrival time for shock waves two to six. From the spectral analysis, the predominant periods for Quepos were 23.2, 29.0, 29.7, and 29.9 min (Fig. 10b), which did not correspond to the first, second, or maximum waves. The maximum wave at Quepos arrived on 15 January at 17:27 with an amplitude of 39.6 cm, a height of 65 cm, and a period of 17 min (Fig. 7). This agrees with the time that the Marina staff reported incidents with yachts returning to the harbor (see next subsection).

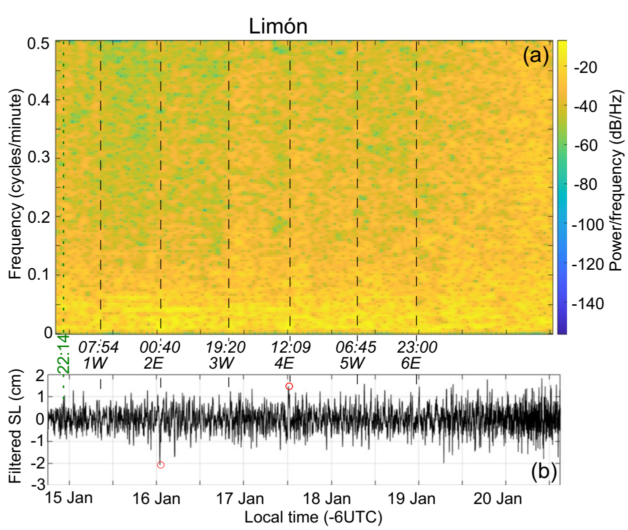

Fig. 8 Limón. Upper panel: spectrogram of the filtered sea level record. Lower panel: filtered sea level record. The green dotted line shows the eruption time. Black dashed lines show the estimated arrival time of the first six shock waves: (1) 15 Jan 07:54 from the west, (2) 16 Jan 00:40 from the east, (3) 16 Jan 19:20 from the west, (4) 17 Jan 12:09 from the east, (5) 18 Jan 06:45 from the west, and (6) 18 Jan 23:00 from the east, calculated from arrival times to the Santa Cruz Meteorological Station. The red circles show the maximum tsunami peak amplitude of 1.5 cm on 17 Jan 12:19 and the maximum trough amplitude of – 2.1 cm on 16 Jan 00:56

The real arrival time of the freely propagating tsunami was sooner than forecasted for Cocos Island and Quepos by about 1 h (Table 1). The estimated arrival time used for SINAMOT reports was obtained using the coordinates of Hunga Tonga–Hunga Ha'apai as the tsunami source and the calculated travel time of an earthquake-generated tsunami at that point. Nonetheless, the freely propagating tsunami did not strictly originate from the volcano, but mainly along the Tonga Trench because of Proudman resonance of the meteotsunami. According to Lynett et al. (2022), ocean depths close to 9 km caused the tsunami amplitude to grow rapidly, as the propagation speeds of the tsunami and the shock wave matched. As the Tonga Trench has widespread depths greater than 9 km, when the atmospheric shock waves passed over it, the resonance created an "energetic beam of energy toward the Americas" (Lynett et al. 2022).

The approximated distance between the Hunga Tonga–Hunga Ha'apai and the Tonga Trench is 188 km. Using the average velocity of the shock wave of 334 m/s, it would take about 9 min for the shock wave to arrive at

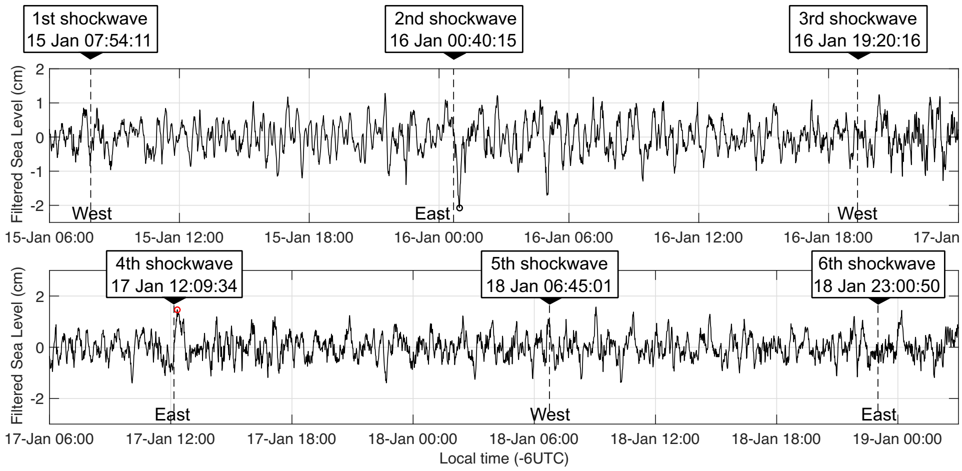

Fig. 9 Filtered marigram at Limón sea level station (Caribbean coast) for 15 to 19 January. Dashed lines show the estimated arrival time for the first six shock waves to the station location, calculated from arrival times to the Santa Cruz Meteorological Station. Odd-numbered shock waves propagated from west to east; even-numbered shock waves propagated from east to west. The dashed-dotted line shows the arrival time of the freely propagating tsunami. The black circle shows the maximum wave amplitude of – 2.1 cm; the red circle shows the maximum mean height of 2.4 cm. The location of the sea level station is shown in Fig. 1

the Tonga Trench and to generate the freely propagating tsunami. On the other hand, the travel time for a freely propagating tsunami between the Hunga Tonga–Hunga Ha'apai and the Tonga Trench is about 1 h, as its propagation velocity depends on bathymetry. This would partially explain the difference between estimated and real arrival times of the freely propagating tsunami at Cocos Island and Quepos stations by about 1 h (Table 1).

According to the spectrograms and the filtered sea level records, the tsunami lasted for more than 48 h at Cocos Island and Quepos (Figs. 4 and 6 and Fig. S5 in the Supplementary Material). This agrees with reports by Cocos Island park rangers of visible sea level fluctuations at the mouth of Genio River and strong currents around the island that persisted for about 2 days. At Quepos, the fluctuations continued for about 72 h which is understandable as this station is in a marina (Fig. 1) and thus is prone to seiches. Past tsunamis have also lasted longer at this station than at other stations considered here (Chacón-Barrantes 2016, 2018; Chacón-Barrantes and Gutiérrez-Echeverría 2017). The shock wave created tsunami pulses at every trench along the Pacific Rim over the course of 12 h, which then overlapped with each other explaining the unusually long duration observed for this event Pacific-wide (Lynett et al. 2022).

Fig. 10 Spectral analysis for sea level records. (a) At Cocos Island, the predominant tsunami periods are 6.77, 6.92, 7.49, and 7.65 min. (b) At Quepos, the predominant tsunami periods are 23.2, 29.0, 29.7, and 29.9 min. (c) At Limón, the predominant tsunami periods are 16.1 and 24.0 min. In all stations, periods smaller than 6 min very likely correspond to background noise

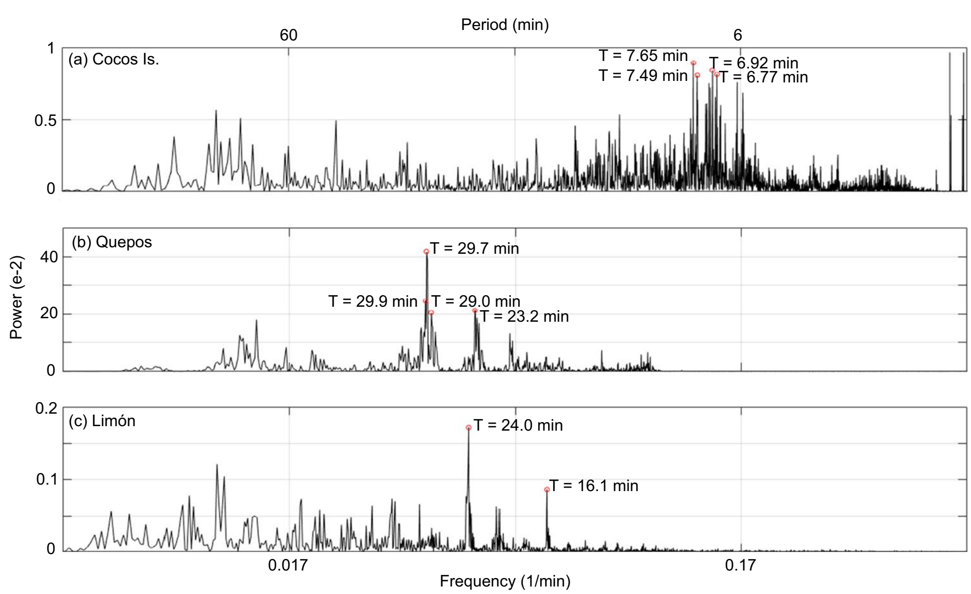

Table 1 Distances between Hunga Tonga–Hunga Ha'apai and the stations, estimated travel times (ETTs), estimated arrival times (ETAs), and characteristics of the tsunami waves at the sea level stations (SLS). The estimated travel times (ETTs) for the shock wave were estimated from the real arrival times to meteorological stations (MetSs). The ETTs and the ETAs for the freely propagating tsunami were calculated using numerical tsunami propagation for a point source collocated with the Hunga Tonga–Hunga Ha'apai volcano, as this is the way it is calculated for earthquakes

	Sea level station	Cocos Island	Quepos	Limón
Distance to HTHH (km)		11,045.62	11,478.57	11,617.52
ETT of the 1st shock wave from HTHH		09:11:05	09:32:41	09:39:36
ETA for the 1st shock wave		07:12:37 15 Jan	07:30:54 15 Jan	07:54:11 15 Jan
First arrival (meteotsunami)	Real arrival time and date (RTA)	07:12:00 15 Jan	08:01:00 15 Jan	08:03:30 15 Jan
	Height (peak-to-trough)	0.98 cm	5.5 cm	1.2 cm
	Amplitude (peak-to-zero)	0.8 cm	3.9 cm	0.9 cm
	Period	7.7 min	20 min	20 min
Second arrival (the freely propagating tsunami)	Estimated travel time (ETT)	13:53:00	14:26:00	-
	Real travel time (RTT)	12:43:00	13:30:00	-
	Difference on travel time	01:10:00	00:56:00	-
	Estimated arrival time and date (ETA)	12:20:00 15 Jan	12:53:00 15 Jan	-
	Real arrival time and date (RTA)	11:10:00 15 Jan	11:56:00 15 Jan	-
	Height (peak-to-trough)	6.7 cm	17.9 cm	-
	Amplitude (peak-to-zero)	3.3 cm	10.7 cm	-
	Period	6 min	29 min	-
Maximum wave	Time and date	23:25:00 15 Jan	17:27:00 15 Jan	12:09:30 17 Jan
	Height (peak-to-trough)	23.2 cm	65.0 cm	2.4 cm
	Amplitude (peak-to-zero)	16.2 cm	39.6 cm	1.5 cm
	Period	5 min	17 min	39 min

Table 2 Arrival time for the peak of the first six shock waves at Santa Cruz Meteorological Station (SCMS), distance from that station to each sea level station (SLS), estimated travel time for the waves between the Santa Cruz Meteorological Station and the SLSs, and estimated arrival time for the peak of the first six shock waves at sea level stations calculated from distances to the Santa Cruz Meteorological Station with an average speed of 334 m/s. Odd-numbered shock waves propagated from west to east; even-numbered shock waves propagated from east to west

	Date	SCMS	Cocos Island	Quepos	Limón
Distance (km) to SCMS			549.5	183.0	283.8
Estimated travel time from/to SCMS			00:27:25	00:09:08	00:14:09
First (west)	15 Jan	07:40:02	07:12:37	07:30:54	07:54:11
Second (east)	16 Jan	00:54:24	01:21:49	01:03:32	00:40:15
Third (west)	16 Jan	19:06:07	18:38:42	18:56:59	19:20:16
Fourth (east)	17 Jan	12:23:43	12:51:08	12:32:51	12:09:34
Fifth (west)	18 Jan	06:30:52	06:03:27	06:21:44	06:45:01
Sixth (east)	18 Jan	23:21:36	23:49:01	23:30:44	23:07:27

Caribbean sea level station

Limón sea level station on the Caribbean coast of Costa Rica was deployed in 1940 but this was the first time it registered a tsunami. The station was not transmitting on 15 January; thus, on 26 January, we visited the site and downloaded the data. Unfortunately, the ocean pressure sensor was damaged and only the radar was recording, the background noise being of the same order of magnitude of the tsunami (Figs. 8 and 9). The freely propagating tsunami (third mechanism explained in the "Methods" section) was not recorded due to distance and energy dissipation.

Nevertheless, in the Limon data spectrogram, very small changes in energy were observed at the estimated arrival times of the shock waves, particularly the second, third, and fourth shock waves for frequencies under 0.4 min^{-1}, corresponding to periods longer than 2.5 min. The highest increase occurred with the fourth shock wave on 17 January at 12:19:30 at frequencies lower than 0.1 min^{-1}, i.e., periods longer than 10 min (Fig. 8a), agreeing with the maximum tsunami height recorded at that time of 2.4 cm, corresponding to an amplitude of 1.5 cm and 39-min period (Fig. 8b). At the estimated time of the second shock wave on 16 January at 00:56:30, the maximum amplitude (trough to zero) of −2.1 cm with a period of 16 min was registered (Fig. 9). This period corresponded with one of the predominant periods obtained with the spectral analysis, i.e., 16.1 and 24.0 min (Fig. 10c).

At Limón, the highest tsunami waves corresponded with east-coming shock waves (second and fourth) which is consistent with the location of the Caribbean Sea in respect to the source and with observations from other Caribbean locations. Sea level stations at west-facing coastlines registered larger tsunamis caused by the first shock wave, coming from the west directly from the eruption (Sostre-Cortes et al. 2022), and stations at east-facing coastlines registered larger tsunamis caused by the second shock wave that came in from the east. During the tsunamis caused by the eruption of Krakatoa volcano in 1883, sea level disturbances at far field sea level stations were reported coinciding with the arrival of "air waves" coming from the sea but not with "air waves" coming from the land (Ewing and Press 1955).

Eyewitness reports

The first arrival of the meteotsunami (generation mechanism #1) was too small to be noticed by the public. The freely propagating tsunami (generation mechanism #3), though, arrived during high tide on the afternoon of a Saturday. Being also the Costa Rican dry season and during the school holidays, many beaches were thus crowded. As no flooding was expected, people were not evacuated from the beaches and social networks such Facebook and Instagram allowed many people to record and distribute their tsunami observations in real time at many locations (see a table of observation points in the Supplementary Material).

From the 22 witness reports, 19 described sea level fluctuations during the most part of the afternoon of 15 January, seven of the reports combining these observations with description of other effects such as strong currents and/or coastal erosion (e.g., Fig. 11a–d). Witnesses reported the "tide" going up beyond the expected high tide level for that day and then receding with periods of between 10 and 15 min. Sixteen of the eyewitnesses' reports were located at Nicoya Peninsula and northern Guanacaste. South of the Nicoya Peninsula, the tsunami was witnessed only in Quepos, Dominical, and Marino Ballena National Park (Fig. 3). We think this geographical distribution of the observations is biased by tsunami awareness and not a geophysical effect.

Strong currents and/or eddies were reported at nine locations, including at Flamingo Marina (location in Fig. 3, pictures in Fig. 11e–g). Flamingo Marina is in Potrero Bay, where Adolfo Barrantes (a Civil Engineer) and his wife Karen Ortiz were on the beach that afternoon and took many pictures and videos. They also measured the tsunami height and inundation distance 55 times from 13:31 until 16:06, with time intervals between 1 and 12 min (Figs. 12 and Fig. 11a and b, the complete dataset is in Table S2 of the Supplementary Material). They used a measuring tape and a laser level with an arbitrary reference level. The data show a maximum tsunami mean height of 1.9 m, representing a horizontal displacement of the water line of 21 m in 14 min, at 14:53. Considering the instrument accuracy and the measuring procedures, the dataset should be assumed as an approximation. However, this is the first time a tsunami is measured in Potrero. Up to date, four tsunamis had been observed in Potrero, representing the highest number of tsunami waves observed by witnesses on the continental Pacific coast of Costa Rica, together with Puerto Jiménez at Osa Peninsula (Chacón-Barrantes et al. 2021b). Specifically at Flamingo Marina, the 1992 Nicaragua and 2011 Japan tsunamis also caused strong currents and some damage (Chacón-Barrantes et al. 2021b). Based on tsunami observations and hazard assessments (Chacón-Barrantes and Arozarena Llopis 2021), Potrero Bay (including Flamingo Marina) is considered a hotspot.

Coastal erosion was reported at 2 locations by witnesses: Marino Ballena National Park and Cocos Island National Park at the mouth of Genio River (Fig. 3D). Marino Ballena National Park has a tombolo, a bar of sand joining a rocky island to the mainland (J.B. Whittow 1984), resembling a whale's tail. During low tide, visitors can walk over the sand bar to the rocky island. The tsunami currents eroded the sand bar, as also happened during the 2011 Japan tsunami (Chacón-Barrantes et al. 2021b), making it impossible to walk to the island during low tide for several days (Fig. 11h). Park rangers reported that by Wednesday 19 January, the sand bar had grown back to its original height and width, and it was possible to walk to the rocky island again during

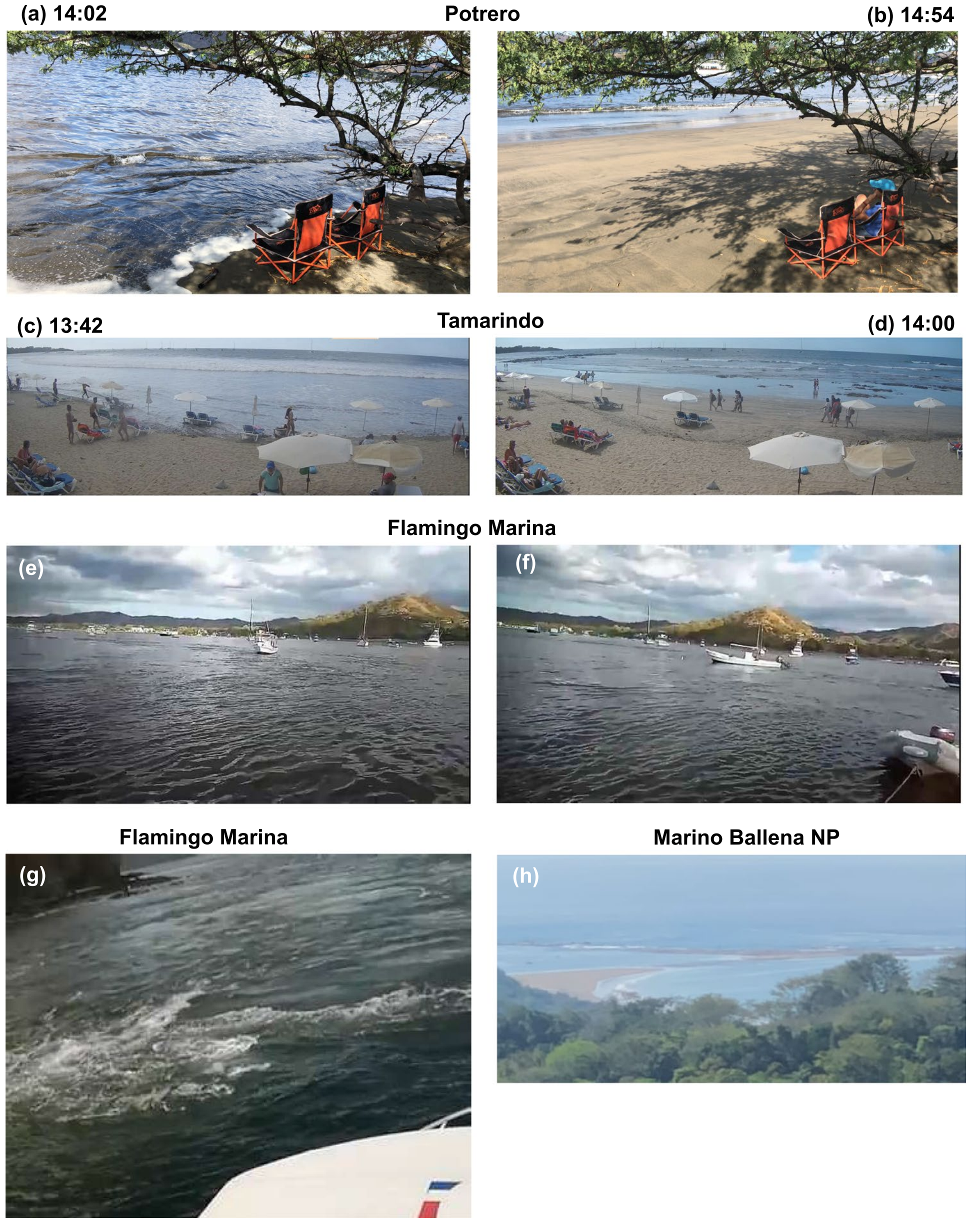

Fig. 11 Tsunami images. **a**, **b** Photos taken by Eng. Adolfo Barrantes at Potrero Beach during the approximate maximum and minimum tsunami amplitudes at 14:02 and 14:54 respectively (see Fig. 12). **c**, **d** Frames taken from the webcam at the Tamarindo Diriá Hotel website during the approximate maximum and minimum tsunami amplitudes at 13:42 and 14:00. **e**, **f** Frames from a video shared by Moisés Contreras Contreras near the entrance of Flamingo Marina during the afternoon of 15 January, all the boats are anchored and there is a difference of 6 s between the two pictures. **g** Frame from a video shared by Moisés Contreras Contreras near the entrance of Flamingo Marina during the afternoon of 15 January showing an eddy generated by the tsunami. **h** Picture shared by Rancho DiAndrew at Costa Ballena Bulletin Board Facebook page of the erosion caused by the tsunami at the middle of the Whale Tail at Marino Ballena National Park

low tide. They reported that the recovery of the sand bar was a progressive process; on Monday, during low tide, they could walk over the sand bar in knee-height water and on Tuesday with ankle-height water, and on Wednesday, the sand bar emerged above the water level as usual. It seems that tsunamis here are erosive events, though the sediment transport recovers its equilibrium within few days once the tsunami currents disappeared.

Cocos Island National Park is located about 530 km offshore of Quepos (Fig. 1A) and has only two beaches: Wafer and Chattam; between those beaches, there is a smaller island named Manuelita (Fig. 3D). Divers reported strong currents in the channel between Cocos and Manuelita islands on Sunday 16 January morning, about 20 h after the first tsunami arrival; this was thus first time a tsunami has been reported at that location. The sea level station in the island is located at Chattam Bay, but most park facilities are located at Wafer Bay, where the Genio River flows into the ocean (Fig. 3D). Park rangers use the river to launch forth their boats as there are no docks on the island. Wafer Bay was the only location in Costa Rica where three tsunami effects were reported for the Hunga Tonga–Hunga Ha'apai tsunami: rangers reported sea level changes, strong currents, and erosion near the river mouth. There have been reports of nine tsunamis observed at the Genio River mouth and Wafer Bay since 1905 (Chacón-Barrantes et al. 2021b; Porras et al. 2022), including the 2022 Mexico tsunami which was not recorded nor observed anywhere else in Costa Rica (NOAA/NCEI 2022). Also, for the two tsunamis recorded at Cocos Island sea level station (the 2021 Kermadec Islands and 2022 Hunga Tonga–Hunga

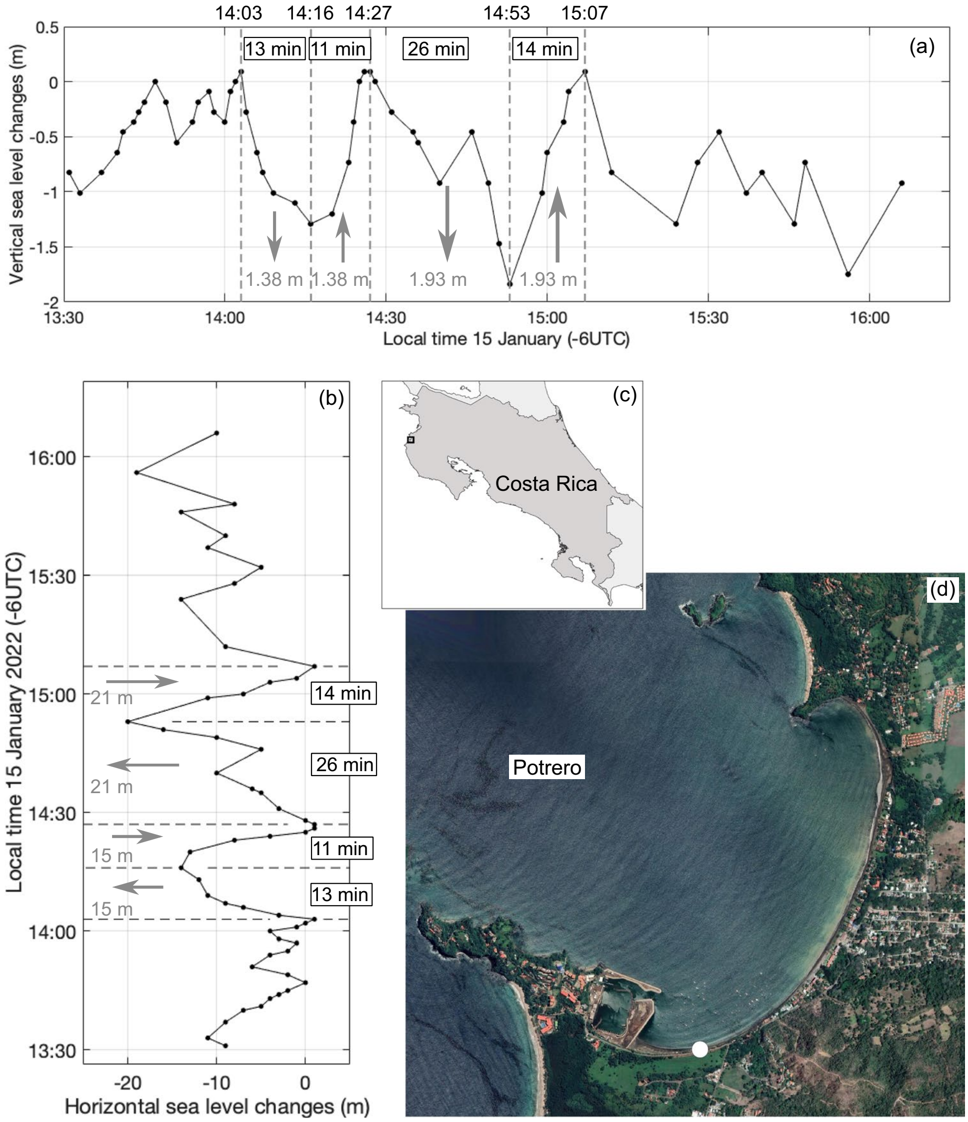

Fig. 12 **a** Vertical and **b** horizontal sea level changes (m) measured manually at Potrero. Zero value was assigned randomly, and the data is not detided. The data was measured at the white dot location in **d**. Location of Potrero in Costa Rica is shown in **c** with a black rectangle

Ha'apai events), the recorded amplitudes were much smaller than those reported for Wafer Bay. Moreover, the rangers stated that the tsunami waves lasted until Monday afternoon in Wafer Bay, by which time the tsunami amplitudes were smaller with larger periods. However, it remained difficult to navigate in and out the river due to strong currents. Thus, we conclude that Wafer Bay and the Genio River mouth should be considered a tsunami hotspot as well.

At seven locations, two combined effects were reported and/or recorded. At Quepos, the sea level station recorded the tsunami and strong currents were reported at and near the Pez Vela Marina entrance. Staff reported several yachts having problems entering the Marina after a competition late on Saturday afternoon. Five locations also reported sea level changes together with strong currents (Bahía Tomás, Potrero, Tamarindo, Cabuya, and Dominical), and Marino Ballena National Park reported sea level changes and erosion.

Discussion

The Hunga Tonga–Hunga Ha'apai tsunamis were observed at some of the hotspots identified to date by tsunami observations and/or through numerical modeling (Chacón-Barrantes and Arozarena Llopis 2021; Chacón-Barrantes et al. 2021b). These include (marked in Fig. 3) Potrero Bay (inset A), Flamingo Marina (inset A), and Tamarindo, Coyote, Quepos, Dominical, Marino Ballena National Park, and Wafer Bay on Cocos Island (inset D). Wafer Bay has nine tsunami observations in history including this tsunami, and all the other locations mentioned above have between three and four tsunami observations in history, also including this tsunami (Chacón-Barrantes et al. 2021b). At some of these hotspots (Quepos, Tamarindo, Marino Ballena National Park and Wafer Bay), the tsunamis were observed for more than 24 h, indicating the presence of trapped waves due to their coastal geomorphology. The identification of such tsunami hotspots allows to prioritize resources on tsunami preparedness and response and to perform a more accurate forecast during an event, including duration of restrictive measures at those places, especially for tsunamis generated by volcanoes for which we have little experience, data, or knowledge.

The freely propagating tsunami (generation mechanism #3) arrived about 13 h after the eruption began. This is in contrast with almost 14 h as estimated for an earthquake-generated tsunami by the models that drive our forecasts (Table 1). Further, SINAMOT was aware of the tsunami threat only 2.5 h before its arrival, due to problems in the upstream warning communication chain. PTWC manually sent threat messages alerting to a tsunami generated by a volcanic eruption, and none of the Central American countries received them. This was a glitch that was already fixed for future events. In addition, SINAMOT was not able to forecast tsunami amplitudes, directivity, and arrival times, as this is only possible for earthquake-generated tsunamis. Despite all of this, SINAMOT was able to activate its alerting protocols and the National Commission for Risk Prevention and Emergency Response (CNE) issued a warning to stop all in-water activity following SINAMOT recommendations. This was 1 h before the arrival of the freely propagating tsunami, but 2:42 h after the shock wave coupled tsunami arrived at Cocos Island. Fortunately, this wave was small enough to be harmless and went unnoticed by the public. The threat level and the warning actions taken in consequence proved to be sufficient for this volcanically generated tsunami at our distal location. However, this is a scenario that is not considered by the generally used seismically sourced tsunami forecast models. PTWC has communicated that for future tsunamis generated by Hunga Tonga–Hunga Ha'apai, they will scale sea level records of the 2022 tsunami to produce the tsunami height forecast (ICG/PTWS 2022). Some countries have developed forecasting methods for tsunamis generated by specific volcanoes, e.g., Stromboli in Italy (Doumaz et al. 2013). Still, for tsunamis generated by other volcanoes, there is no general procedure or method to forecast tsunami heights, at any basin. This handicap and the development of procedures for warning of tsunamis generated by volcanoes are currently addressed by the global tsunami warning system with the creation of an Ad Hoc Team on Tsunamis Generated by Volcanoes during the Fifteenth Meeting of the Working Group on Tsunamis and Other Hazards Related to Sea-Level Warning and Mitigation Systems (UNESCO/IOC 2022b).

Once we alerted of the event, the warning dissemination worked well for many places in Costa Rica, particularly for those where tsunami evacuation maps already existed. In communities that have already experienced at least one tsunami awareness activity during the past 6 years (e.g., through tsunami presentations, creation, and distribution of tsunami evacuation maps; see Table 1 in the Supplementary Material), the response was also good. This highlights the importance of performing tsunami awareness activities and exercises at all levels and for preparing and distributing tsunami evacuation maps and plans, so the coastal communities are prepared and know what to do when a tsunami warning is issued.

This point is stressed by the fact that the eyewitness reports on the mainland were from regions included during the first stage of the SINAMOT project aimed at preparing and distributing tsunami evacuation maps. Twelve of the 20 eyewitness reports on the mainland were from communities that already had a tsunami evacuation map; seven of them were from communities also having tsunami evacuation route signage. The remaining eight reports were from neighboring communities. Thus, installing tsunami evacuation route signs and information panels is an important part of preparation.

All current recognized UNESCO/IOC Tsunami Ready communities responded properly and promptly to the warning, including Quepos, although it was not officially recognized as Tsunami Ready at that time. All Tsunami Ready communities reported observing the tsunami, except for El Coco, where persons from the local emergency committee went to the beach but were not able to observe the tsunami. Becoming UNESCO/IOC Tsunami Ready is a process that could take up to several years, and Costa Rica has many communities at different stages of that process. However, all responded properly and in a timely manner. In comparison, several communities that only had tsunami evacuation maps did not perform any action after the tsunami warning. This was particularly true for those communities not having a local emergency committee.

Increased preparedness of UNESCO/IOC Tsunami Ready communities, current and in progress, raised awareness in neighboring communities allowing the local authorities to respond as expected and for communities to follow the instructions issued by the authorities and identify the tsunami.

However, for this event, it was not possible for first responders and emergency committees to cover all Pacific beaches in Costa Rica in the required timespan. Many beaches are isolated and/or their neighboring communities lack tsunami preparedness. This is an issue that should be addressed, particularly by municipal and local emergency committees. Fortunately, none of these places corresponded to hotspots, but the Hunga Tonga–Hunga Ha'apai tsunami revealed that warning dissemination is the weakest link in the Costa Rica tsunami warning system.

The highest tsunami amplitudes, caused by the freely propagating tsunami, arrived after the original forecasted time, and these were the waves observed by eyewitnesses during high tide early on Saturday afternoon. Nevertheless, strong currents were observed at some hotspots also during Saturday evening and in some cases through Monday, particularly during high tide. In Tamarindo (Fig. 3), lifeguards reported an unusually high number of people being rescued from rip currents on Sunday. On Cocos Island, strong currents were observed also during Monday. Therefore, authorities must consider extending the duration of tsunami warnings related to currents for up to several days at least at hotspots.

Costa Rica is a highly visited tourist destination (Van Noorloos 2011; Nost 2013); thus, language barriers can play a role on warning dissemination (Peguero 2006; Clerveaux et al. 2008; Arlikatti et al. 2014). For example, park rangers from the Manuel Antonio National Park, on the Central Pacific coast, reported problems communicating the warning especially in giving the instructions to tourists who did not speak Spanish. SINAMOT and CNE are working on designing a portable sign, with multilingual recommendations, that can be used by non-English-speaking park rangers and first responders nationwide during a tsunami warning.

Moreover, the Hunga Tonga–Hunga Ha'apai tsunami showed the importance of international collaboration and communication, particularly that driven by direct and real time communication and information exchange, for example, through instant messaging such as WhatsApp.

The Hunga Tonga–Hunga Ha'apai tsunami was also recorded at the Acajutla sea level station in El Salvador, with a maximum amplitude of 26 cm. The tsunami was also observed as sea level fluctuations without flooding in Cedeño, Honduras. At the Guascorán River in Honduras, fishermen reported that the sea entered the river with currents stronger than usual (NOAA/NCEI 2022). All other Central American countries did not report any observations of this tsunami. The magnitude of the tsunami record in Acajutla and of the witnesses' reports in Honduras is comparable to what was widely observed in Costa Rica. Also, the reports from Cedeño come from the first UNESCO/IOC Tsunami Ready community in Central America, recognized in 2017.

Given our experience, preparations for tsunamis from Hunga Tonga–Hunga Ha'apai future eruptions are currently being made. ICG/PTWS has prepared a document, entitled "PTWC Interim Procedures and PTWS Products for Tsunamis from the Hunga Tonga–Hunga Ha'apai Volcano" (ICG/PTWS 2022) in which it is stated that "NTWCs (National Tsunami Warning Centers) will need to apply their knowledge of what happened along all their coasts during the 15 January event and also scale it accordingly." Thus, details given here are a valuable source of information in case of future Hunga Tonga–Hunga Ha'apai eruption-related tsunamis impacting coastlines in Central America. For scaling future eruptions, ICG/PTWS recommends use of barometric pressure records. As a result, the National Meteorological Institute of Costa Rica should consider increasing the sample rate at barometric sensors and enable more stations to transmit in real time or to allow remote access of the data for tsunami warning purposes.

Conclusions

The tsunami generated by the eruption of Hunga Tonga–Hunga Ha'apai represented a challenge for tsunami warning systems, at regional, national, and local levels. In Costa Rica, this event was the first representing a threat since the creation of SINAMOT (*Sistema Nacional de Monitoreo de Tsunamis*, National Tsunami Monitoring System). The tsunami thus allowed the country to test the threat assessment and warning communication protocols and communication procedures end to end. The communication line runs from SINAMOT through CNE (*Comisión Nacional de Prevención de Riesgos y Atención de Emergencias*, National Commission of Risk Prevention and Emergency Response) to municipal and local emergency committees, first responders, and potentially impacted population. Despite all efforts, many people on beaches at the time of tsunami arrival had not received the warning. We thus need to improve warning dissemination at all levels.

However, even though Costa Rica did not receive PTWC (Pacific Tsunami Warning Center) messages, CNE assisted by SINAMOT was able to issue a warning indicating a low threat level more than an hour before the arrival of the larger waves caused by the freely propagating tsunami, and no casualties or damage were reported. In Costa Rica, the tsunami was observed or recorded at 24 locations, including at the three existing sea level stations of which two are in the Pacific and one is in the Caribbean. Witness observations were reported at 22 locations along the Pacific Coast, including at the site of one sea level station. The tsunami did not cause any flooding, yet strong currents, coastal erosion, and sea level fluctuations were observed by eyewitnesses, including the dataset of time-varying tsunami height and inundation distance measured manually at Potrero during the tsunami. The Potrero dataset is the first one for that location even though it is considered a tsunami hotspot based on tsunami observations and results from numerical modeling. Also, it represents an important example of citizen science.

This event thus increased tsunami awareness for Costa Rican people and provided an opportunity to test and review protocols and procedures both at national and local levels. The evaluation of the event response allowed SINAMOT and CNE to improve their protocols and products and to include tsunamis generated by volcanoes in these protocols and products.

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Declarations

Conflict of interest The authors declare no competing interests.

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