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Worldwide Signature of the 2022 Tonga Volcanic Tsunami

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Key Points:

- Analysis of 589 tide gauge records reveals the spatiotemporal features of the 2022 Tonga volcanic tsunami around the world oceans and seas
- The leading wave was ubiquitously small, and its early arrival suggests it was caused by a moving air pressure wave produced in the explosion
- The largest waves were concentrated in the Pacific with occurrence times consistent with an origin in the vicinity of the volcano

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The eruption of the *Hunga Tonga-Hunga Ha'apai* Volcano in January 2022 in the southwest Pacific islands of Tonga triggered a tsunami that was detected beyond the Pacific basin. Here we show its spatiotemporal signature as revealed by hundreds of publicly available coastal tide gauge records from around the world. The Tonga tsunami was characterized by a uniformly small leading wave that arrived earlier than theoretically expected for a tsunami wave freely propagating away from the volcano. In contrast, the largest waves, of up to +3 m high, were concentrated in the Pacific and their timing agrees well with tsunami propagation times from the volcano. While the leading waves were caused by a previously reported fast-moving atmospheric pressure pulse generated in the volcanic explosion, the large waves observed later in the Pacific were likely originated in the vicinity of the volcano although its generation mechanism(s) cannot be identified by the tide gauge data alone.

Plain Language Summary

In January 2022, a submarine volcano in the southwest Pacific islands of Tonga erupted and triggered a tsunami that was detected at many places, even outside the Pacific Ocean. The Tonga tsunami was recorded by hundreds of coastal stations that continuously measure the sea level around the world. Here, we analyze such records to provide a global picture of this tsunami. We found that the up and down movements of the sea surface (tsunami waves) around the Pacific coast were distinctly different than those at other parts of the world. The Pacific measurements feature small tsunami waves before the occurrence of much larger waves. Outside the pacific we mainly see these small first waves that do not grow too much afterward. Because the timing of these first waves coincides with the passing of a previously reported atmospheric pressure wave generated in the volcanic explosion, we think they were caused by interactions between the air and seawater. This is why we also see them outside the Pacific. In turn, the much larger waves at the Pacific were likely originated in the vicinity of the volcano. This is why we do not see them elsewhere.

1. Tide Gauge Observations of the Tonga Tsunami

On 15 January 2022, at 4:14:45 UTC (17:14:45 local time), an explosive eruption of the *Hunga Tonga-Hunga Ha'apai* Volcano (U.S. Geological Survey, 2022), in the Islands of Tonga in the southwest Pacific Ocean, triggered a tsunami that prompted the issuance of tsunami alerts around the world (Titov et al., 2022). The Tonga tsunami was widely recorded by a global network of coastal tide gauge stations, which detected conspicuous tsunami waves not only in the Pacific Ocean, but also in the Atlantic and Indian oceans, and in the Caribbean and Mediterranean seas (Fountain, 2022). The rare origin and far-reaching nature of this tsunami compared to those frequently triggered by subduction zone earthquakes highlight the scientific and societal need for a better understanding of this event.

In this paper we present the worldwide signature of the Tonga tsunami as revealed by coastal tide gauge data. The purpose is to show the spatiotemporal characteristics of a volcanic tsunami on the world coasts and to provide valuable evidence to be used in dedicated tsunami source studies. We analyzed 831 tide gauge records publicly available via the Intergovernmental Oceanographic Commission of UNESCO (http://www.ioc-sealevelmonitoring.org/). Specifically, we (a) downloaded the time series, (b) selected those with reliable data (589 out of 831) from a supervised algorithm that identifies and assess data quality parameters (e.g., size and location of gaps), (c) extracted the tsunami signal by bandpass filtering in the tsunami frequency band (provided in digital format in Dataset S1, and (d) calculated the arrival time and crest-to-trough height of both the leading and largest tsunami waves by combining an automatic algorithm based on signal-to-noise ratio with a visual inspection. The

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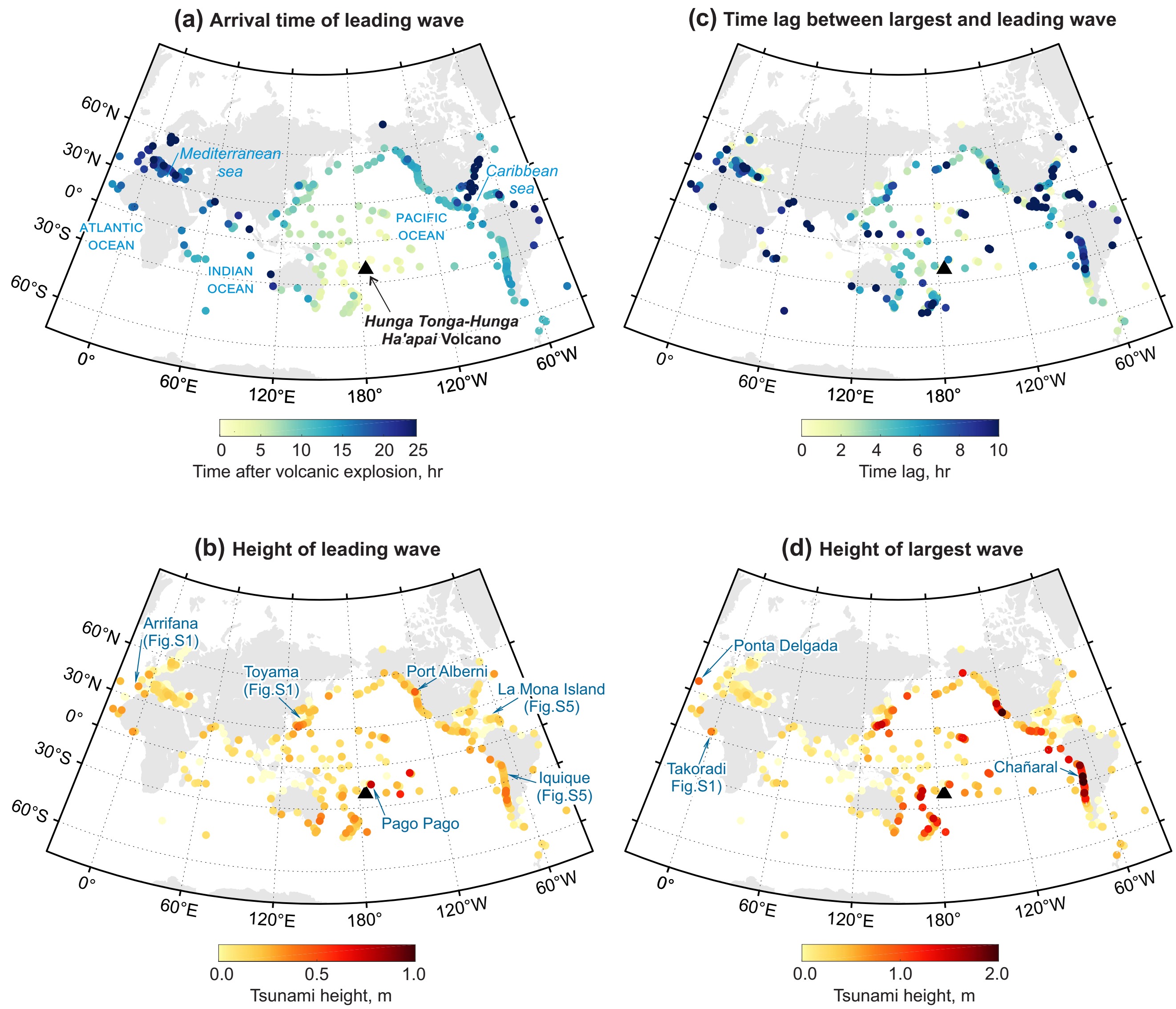

Figure 1. The spatiotemporal signature of the January 2022 Tonga tsunami as derived by coastal tide gauge measurements around the world. (a) Arrival time of the leading wave at each station relative to the time of the explosion of the *Hunga Tonga-Hunga Ha'apai* Volcano reported by the U.S. Geological survey (4:14:45 UTC). (b) Crest-to-trough height of the leading wave. (c) Time of occurrence of the largest wave relative to the arrival time of the leading wave. (d) Crest-to-trough height of the largest wave. The black triangle indicates the location of the *Hunga Tonga-Hunga Ha'apai* Volcano, and the blue arrows in (b) and (d) indicate the locations of stations mentioned in the text and/or figures. The source data for this figure is available in Table S1 in Supporting Information S1.

procedure is described in Text S1 and Figure S1 in Supporting Information S1, and the main results are presented in Figure 1.

With a few exceptions, the arrival time of the leading tsunami wave gradually increased with distance to Tonga (Figure 1a). Their heights were usually smaller than half a meter and rather uniform among stations regardless of their distance to Tonga (Figure 1b). However, higher than average leading waves were estimated at some places. While higher leading waves near Tonga (e.g., Pago Pago; Figure S2 in Supporting Information S1) are likely real, those at distant locations (e.g., Port Alberni; Figure S2 in Supporting Information S1) may be not but instead represent subsequent waves because the leading waves were not conspicuous enough to be reliably identified by our method.

The spatiotemporal signature of the largest waves differs from that of the leading waves. First, in most stations, the temporal occurrence of the largest waves was generally independent on the arrival of the leading waves, with time lags ranging from 0 to +10 hr (Figure 1c). Second, the height of the largest waves varied significantly among stations, with the largest waves concentrated in the Pacific (Figure 1d). Although not as big as the largest tsunami heights observed in the Pacific (reaching up to 3.4 m at Chañaral, Chile; Figure S2 in Supporting Information S1), tsunami waves as high as a meter were observed in the Atlantic Ocean such as in Takoradi, Ghana (0.9 m; Figure S2 in Supporting Information S1), and Ponta Delgada, Portugal (1.1 m; Figure S2 in Supporting Information S1), both located near the antipode of Tonga.

2. Complex Source of the Tonga Tsunami

The tide gauge evidence confirms the previously recognized atmospheric source mechanism for the leading waves observed across the world and sheds some light on the possible complex sources of the larger waves occurring later in the Pacific coasts.

A remarkable feature of the Tonga tsunami is the generally small and uniform height of the leading wave across the world oceans and seas, a signature that earthquake-triggered tsunamis usually lack. As previously recognized, their arrival times at most stations are much shorter than theoretically expected for a tsunami wave freely propagating away from Tonga (Figure S3 in Supporting Information S1) and instead coincide with the passing of a

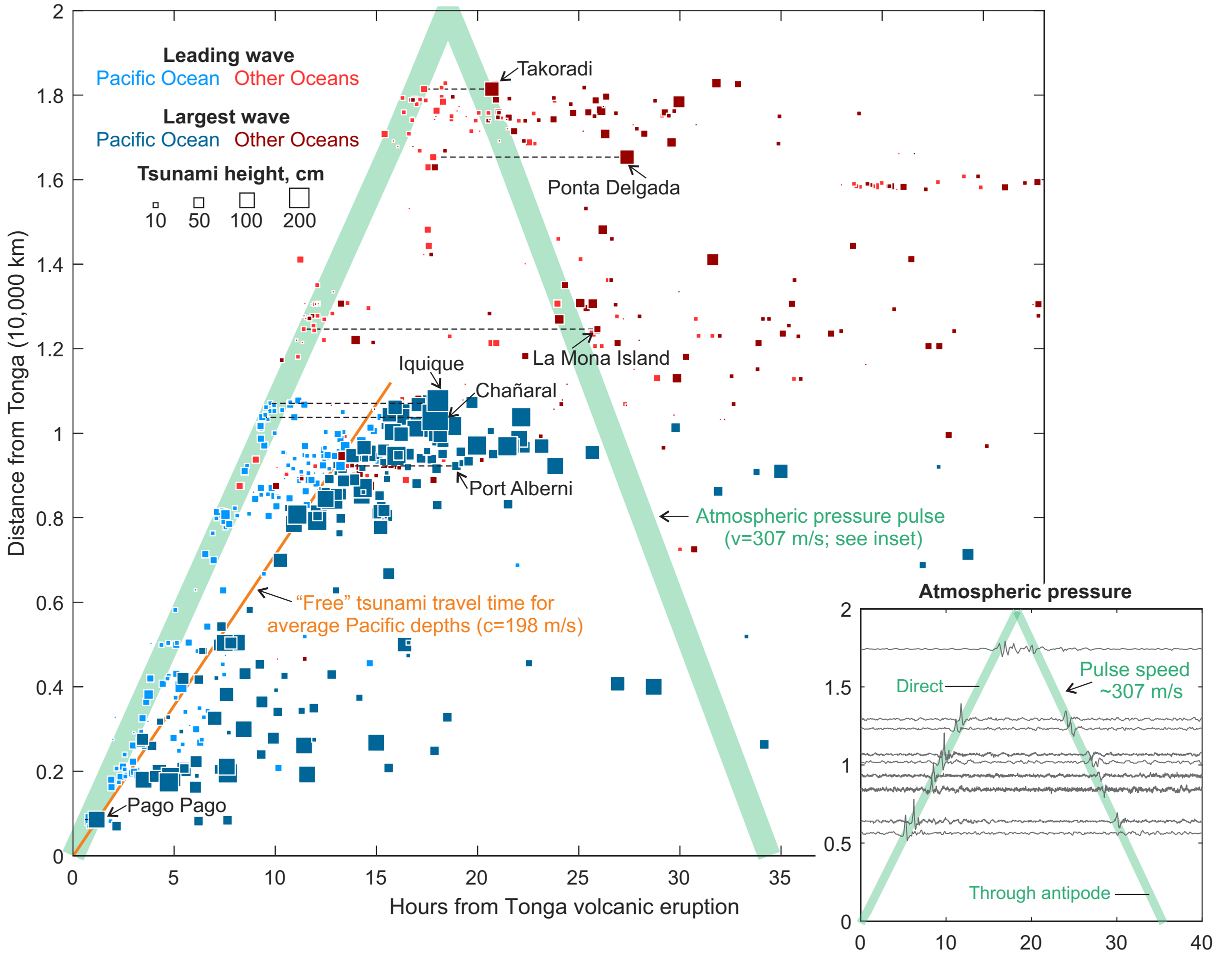

Figure 2. Aggregated results of tsunami arrival times in comparison with the estimated passing time of an atmospheric pressure pulse generated in the volcanic explosion (green band) and the theoretical arrivals to the Pacific coasts of a tsunami originated in Tonga (orange line). The estimated average speed of the passing atmospheric pressure pulse, of ~307 m/s, was inferred from the 9 atmospheric pressure records shown in the inset, with details in Figure S4 in Supporting Information S1. The orange line indicates the propagation times of a tsunami (free long wave) traveling over the average Pacific water depths (i.e., 4,000 m) and is shown for reference (see Figure S3 in Supporting Information S1 for more precise numerical calculations of arrival times from Tonga to the continental borders assuming realistic bathymetry). The horizontal dashed lines connect the arrival times of the leading (left end) and largest (right end) waves for stations mentioned in the text and/or figures.

fast-moving atmospheric pressure wave generated in the volcanic explosion (Adam, 2022) for which we estimated a speed of 307 m/s (Figure S4 in Supporting Information S1). The travel time correspondence between the atmospheric pulse and leading tsunami wave clearly seen in Figure 2 confirms the atmospheric origin of the leading waves observed in most of the stations worldwide. A similar atmospheric mechanism was invoked to explain sea-surface perturbations recorded at different oceans following the 1883 Krakatoa Explosion in Indonesia (Press & Harkrider, 1966).

However, the tide gauge evidence alone cannot conclusively determine whether the moving atmospheric pressure pulse was also the main source of the larger waves occurring later in the Pacific or additional generation mechanisms were involved. There are two main arguments that seem to favor the contribution of a generation mechanism localized in the vicinity of the volcano. The first are the distinct global signatures of the leading and largest waves. While the leading wave heights were generally uniform across the world oceans and seas (Figure 1b and Figure S5 in Supporting Information S1), the largest waves were systematically larger in the Pacific basin (Figure 1d). Unless the particular geomorphology of the Pacific basin played a role, the global patterns of leading and largest waves should not have been as different if the moving atmospheric pulse was the main source since its amplitude was similar everywhere (Figure S4 in Supporting Information S1). The second is the temporal agreement of the largest waves occurring later in the Pacific coasts with the theoretical travel times of a free tsunami wave originated in the vicinity of the volcano at the eruption time, which for the average Pacific water depths can be approximated using a mean wave speed of 198 m/s (orange line in Figure 2). Specifically, unlike the leading waves, the largest waves observed in the Pacific coincided with or occurred systematically after the theoretical travel times of a tsunami freely propagating away from the volcano via the oceanic path (Figure 2). This temporal correspondence is not seen as clearly at stations outside the Pacific, where the largest waves generally occurred before the theoretical travel times from Tonga (Figure S3 in Supporting Information S1) and usually coincided with or occurred after the first or second passing of the atmospheric pressure pulse (Figure 2 and Figure S5 in Supporting Information S1). While the above suggests that the largest waves were originated in the vicinity of the volcano, the tide gauge evidence alone cannot identify their dominant generation mechanisms neither can rule out additional contributions from atmospheric forcing processes.

The unusual signature of the Tonga tsunami around the world reflects the complexities of the volcanic, atmospheric and oceanic processes that generated it and demonstrate the potentially global-scale impact of volcanic tsunami hazards. We believe that the results presented here will provide valuable data to improve their understanding.

Data Availability Statement

The source data of Figures 1 and 2 is provided in Table S1 in Supporting Information S1, and the processed sea-level time histories shown in Figure S2 in Supporting Information S1 are provided in digital format in DataSet S1, both available at https://watershed.sdsu.edu/research. The raw sea level records are available in http://www.ioc-sealevelmonitoring.org/.

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