

Atmosphere-solid earth coupling signals generated by the 15 January 2022 Hunga-Tonga eruption

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The January 15th 2022 eruption of the Hunga-Tonga volcano was associated to one of the highest energy volcanic explosions of the past few decades. Here we present a compilation of data from global seismic networks to explore three main topics: the time evolution of the eruption, the propagation of the atmospheric waves around the Earth and the low-frequency, long-lasting seismic signals worldwide after the main event. We find that the eruption started around 04:00, included two large explosions at 05:30 and 08:25 and produced atmospheric waves which circled the Earth more than two times during a time span of 3.5 days and were detected seismically. We also identify very low frequency signals, detected over several hours, which we interpret as resulting from the excitation of Earth normal modes. To our knowledge, there are no previous examples of atmospheric-solid Earth coupling over such a long time interval and only two examples of normal mode excitation following volcanic eruptions.

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The Hunga-Tonga volcano, located in the South Pacific Ocean, began its recent activity on December 20, 2020 with multiple explosions and a high ash plume¹. After a period of relative calm, a powerful explosion devastated much of the island on January 14, 2022, followed on January 15 by the main eruptive event, which becomes one of the most powerful volcanic events recorded to date, with an energy release estimated between 4 and 18 megatons of TNT². The eruption released material as high as 50–55 km in altitude³, producing a plume reaching 600 km in diameter, and generating, among other effects, a tsunami detected on the Pacific coasts, strong ionospheric disturbances⁴, up to 700,000 volcanic lightning strikes⁵ and a strong acoustic explosion in the atmosphere, which was heard as far as central Alaska, more than 9700 km away. Preliminary estimations attribute a VEI value of 5–6 to the eruption^{5,6}. The variation in atmospheric pressure generated by this explosion has spread throughout the planet, producing variations that have been detected by various types of sensors, from barometers integrated in weather stations to geodetic stations⁷. This wave has been interpreted as a Lamb wave, a non-dispersive atmospheric wave with purely horizontal motion, which propagates at speeds close to 0.310 km/s, slightly slower than the speed of sound, and optimally transfer energy over large distances⁸.

In this contribution we investigate the seismic signals generated by the Hunga-Tonga eruption recorded in global scale seismic networks, focusing on three key points; (i) a description of the temporal evolution of the eruptive process derived from the analysis of seismic data, (ii) the seismic signals generated by the passage of the atmospheric wave during its successive circumambulations around the Earth, and (iii) the observation of low-frequency signals during the hours following the eruption, interpreted as the result of the excitation of the Earth's normal modes due to the volcanic explosion. The first point will allow us to better define the evolution of the eruptive process, while the two other observations must be qualified as exceptional, since there are no previous references to worldwide seismic recordings of atmospheric disturbances for such an extensive period of time, with only a couple of precedents, most recently 40 years ago, from normal mode excitation resulting from volcanic eruptions.

Results and discussion

Temporal evolution of the Hunga-Tonga eruption. Using the time arrivals of body seismic waves at seismic stations around the world, the USGS seismic catalogue (<https://earthquake.usgs.gov/earthquakes>) reported the location (20.546°S, 175.390°W) and origin time (2022-01-15 04:14:45 UTC) of the eruption, and assigned an equivalent seismic magnitude of 5.8, corresponding to a moderate size earthquake. This magnitude is based on the evaluation of the amplitude of Rayleigh surface waves at a period near 20 s, a technique calibrated for earthquakes that can only be considered as a preliminary estimate of the size of the volcanic event. Prior to this event, the ISC catalogue (International Seismological Centre (2022), On-line Bulletin, <https://doi.org/10.31905/D808B830>), gathering information from seismic and infrasound networks, reports minor events with locations near the Hunga-Tonga volcano at 04:06:13, 04:07:53, 04:12:54 and 04:13:47, detected only at a limited number of stations. From the analyses of satellite images, Carr et al.³ and Kumar Gupta et al.⁹ reported that the eruption became visible just after 04:00 UTC. Yuen et al.⁵ have used infrasound data to conclude that the eruption began at 04:02 UTC $\pm$ 1 minute, while the Lamb wave emerged at 04:15 $\pm$ 2 min. In order to explore if this volcanic activity preceding the main explosion can be identified in seismic data, we apply a low-frequency filter to the signals recorded at the closest stations in our dataset, located at distances between

750 km and 2485 km from the Hunga-Tonga volcano. Figure 1a shows a previously unreported low-frequency arrival at 04:02 at FUTU, the closest station, preceding the main phases arriving around 04:16 (Fig. 1a, blue dashed lines). This early phase, with a low-frequency content ranging between 0.02 and 0.08 Hz, is observed at consistent times in the neighbour stations. The spectrograms of this early arrival show a continuous frequency content around 0.1 Hz, with the largest pulse (arriving at 04:05:30 at FUTU) showing frequencies extending between 0.01 and 0.08 (Supplementary Fig. 1a) in the range of the Very-Long Period (VLP) events¹⁰. In order to better characterize the signal, we have analyzed its particle motion diagrams, that show an elliptical motion in the vertical-radial plane indicative of a Rayleigh wave, which is very similar to the motion during the main phase arrivals (Supplementary Figure 1b). Although the amplitude of these early arrivals is small relative to the main event, the fact that they were recorded at distances greater than 750 km indicates that they are due to a process that involves an important energy release. We interpret that this early arrival, low-frequency seismic signals are due to the first stages of the volcano eruption, involving movement of magma prior to the main explosion.

The most energetic arrivals, consistent with the origin time reported in global seismic catalogues, show a complex waveform, with two energy packets with similar waveforms, separated by about 200 s (Fig. 1a). The first packet, lasting around 60 s, looks as a single pulse, while the second one, lasting nearly 3 minutes appears as more complex. In both cases, the spectrogram shows that these pulses contain frequencies between 0.01 and 0.08 Hz, similar to those discussed previously for the early arrival (Supplementary Fig. 1b) and can be described as Very-Long Period (VLP) events. Yuen et al.⁵, have studied these arrivals using teleseismic P-wave arrival stacking, interpreting them as the result of 4 sub-events with similar waveforms, the last three forming the second energy packet described here. These authors interpret the similarity of waveforms as the effect of episodic eruptive activities with the same characteristics. We have verified that for the stations located at distances between 750 and 830 km of the volcano there is an excellent agreement between the first VLP pulse and the signals arriving 184 s, 224 s and 228 s later (Supplementary Fig. 2), confirming then the presence of episodic repetitive source of activity.

The ISC catalogue reports a magnitude 4.7 event at 05:30 close to the Hunga-Tonga volcano, that results in a low-frequency signal arriving around 05:33 UTC at the closest stations (Fig. 1b, brown dashed lines). As seen in Fig. 1c, the move-out and the decrease in amplitude of the signal related to this event are similar to those of main signal, denoting that they share the same source area. Arrivals corresponding to this event can be detected at distances near 15,000 km, when they overlaps with the coda of the main event. This event can be related to the lower-altitude umbrella cloud identified in the Himawari-8 geostationary satellite data around 05:30⁹.

Later on, a third highly energetic signal, arriving at 08:28 to FUTU, approximately 4.25 hours after the main event, can be identified in stations distributed all over the planet, but it is not included in the ISC catalogue. Again, the move-out and the decrease in amplitude of this signal are similar to those of main signal (Fig. 1c). The infrasound results gathered by Matoza et al.⁷ includes an event at 08:31 which could be related to the observed signal, although the reported origin time should then be corrected, as the seismic station shows clear arrivals before this time. Carr et al.³, analysing data from the GOES-17 satellite, reported that an overshooting plume core reached the upper stratosphere at 08:41. Satellite data analysed by Kumar Gupta et al.⁹ have also shown a plume overshoot between 08:10 and 08:30 UTC. These plumes clearly appear to be the result of the

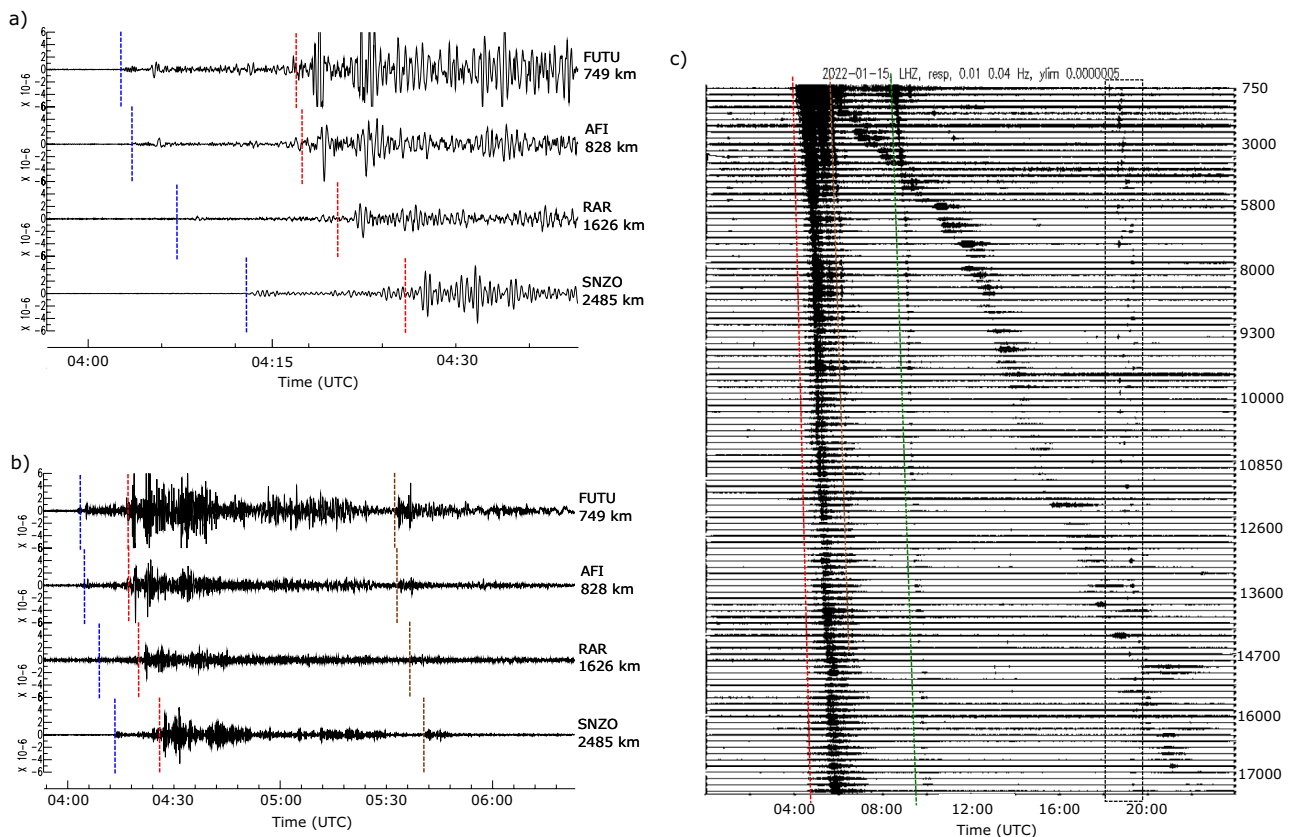


Fig. 1 Seismic records of the Hunga-Tonga eruption. Instrumental response has been removed, data have been filtered between 0.01 and 0.04 Hz and plotted without amplitude normalization. The amplitudes of the signals are expressed in m/s and the traces are ordered according to their epicentral distance. **a** Detail of the signal onset at the closest stations. Red dashed line shows the most energetic arrival, compatible with the origin time in seismic catalogues. Blue dashed line shows the first arrival observed in the filtered data. The labels indicate the name of the station and the distance to the origin. **b** Larger-scale view of the same dataset, showing the arrival from a second event detected around 05:30 (brown dashed lines). **c** Seismic traces for the entire dataset during January 15, 2022. Red line shows the main arrival, brown line the phases related to the 05:30 event and green line those related to the event detected around 08:25. The black box shows the arrivals from a 5.7 magnitude earthquake with epicentre in the Pacific-Indian Ridge. The signal observed in intermediate times propagating with slow apparent velocity, corresponds to the atmospheric wave and will be discussed in the following section. Labels on the right side show the approximate epicentral distance, expressed in kilometers.

seismically detected explosion. In order to estimate which could be the seismic magnitude of this event, we have inspected the phase arrival readings in the ISC bulletin during a period of six months, to conclude that most of the events recorded at distances over 15,000 km, have seismic magnitudes larger than 4.6–4.8. As the Hunga-Tonga event with origin time near 08:25 can be detected at distances up to 17,700 km (Fig. 1c) we can estimate that its seismic magnitude should be above this range. The frequency content of the signal, restricted to the frequencies under 0.05 Hz, can probably justify that this event does not appear in seismic catalogues.

We can state that during the first hours of the Hunga-Tonga eruptive process there were three large explosions detected seismically worldwide, a main event with origin time around 04:15 UTC and two later events around 05:30 and 08:25. In order to study the similarity between the VLP pulses in the three main events, we have followed the same procedure described previously for the study of the sub-pulses of the main event. Supplementary Figure 3 shows that, although the full waveform of the three events is not identical, there is an excellent correlation between the VLP pulses of the main event and those of the 05:30 and 08:25 events, in spite of their very different amplitude values. Therefore, the presence of similar volcanic activity sources acting several times, proposed to explain the sub-pulses of the main event, can now be extended from the range of few minutes

discussed above to the range of several hours. VLP events with frequencies between 0.01 and 0.5 Hz have been observed in many volcanoes since the beginning of the deployment of broadband seismometers and have been usually associated with perturbations in the flow of magma and gases through conduits¹⁰. Fontaine et al.¹¹ reported cyclical VLP events prior to and during the collapse of the Piton de la Fournaise caldera (La Reunion island) in April 2007, proposing that they could result from repeating piston-like collapses through a structure surrounding a magma reservoir. Further modelling work will be needed to check if this kind of interpretation can apply to the Hunga-Tonga eruption.

Seismic recording of the atmospheric wave. The Hunga-Tonga eruption generated an atmospheric Lamb wave detected throughout the world by different types of sensors, including broadband seismic stations. Figure 1c shows the signal induced by the passage of this wave, which here appears as a high-amplitude, low-frequency signal with a duration greater than one hour. As Lamb waves propagate with a speed close to 310 m/s, an order of magnitude slower than seismic waves, their delay time with respect to seismic arrivals increases strongly with distance, being detected in the most remote stations about 16 hours after the moment of the explosion.

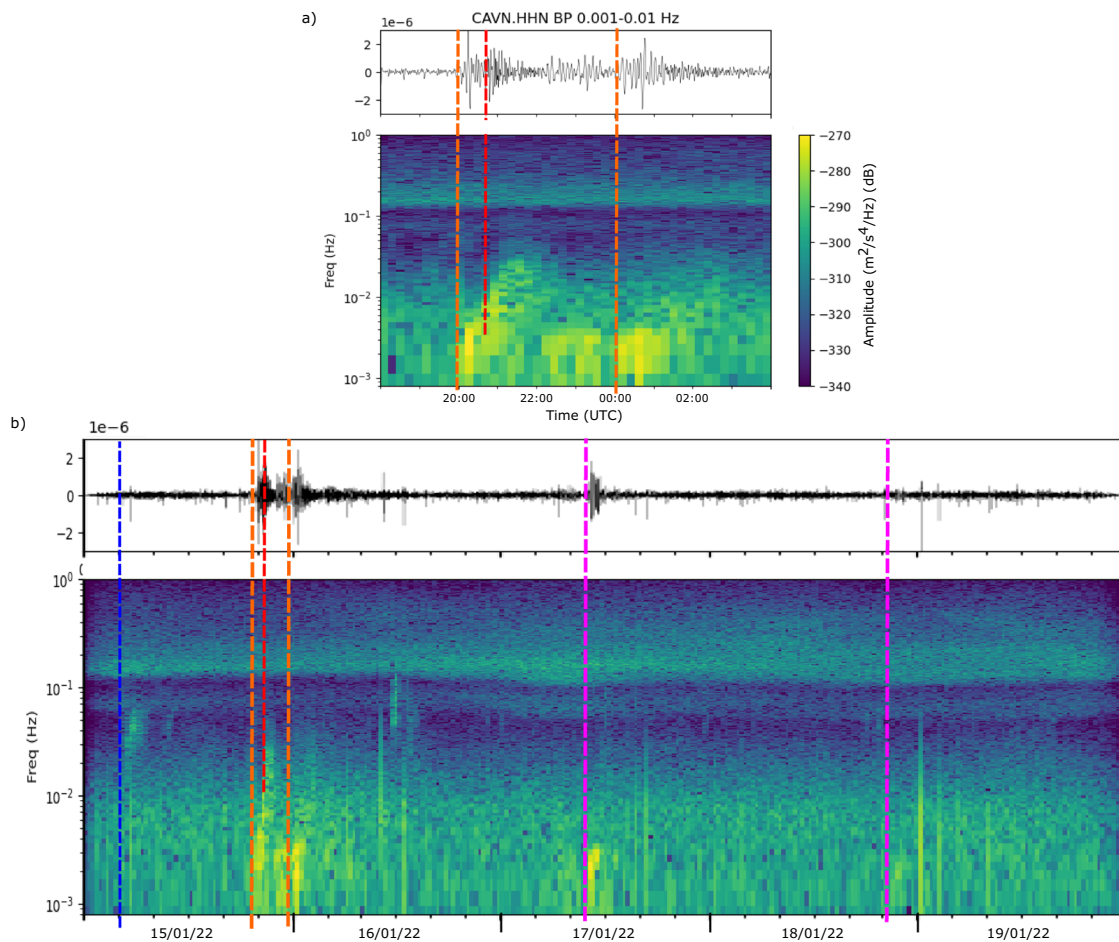


Fig. 2 Seismic signals related to the atmospheric wave recorded at station CA.CAVN (NE Iberia). **a** Arrival of the first atmospheric waves. Orange lines show the arrival of the Lamb waves travelling along the short and long path of the great circle. Red dashed line shows the arrival of the dispersive wave. **b** Five days of seismic signal and spectrogram at the same station. Blue dashed line shows the arrival of the seismic waves. Orange and red dashed lines show the first arrivals of the atmospheric waves. Purple lines shows the record of the atmospheric waves after successive circumambulations of the Earth. The instrument response has been removed and the seismic trace has been band-pass filtered between 1 and 10 mHz. The data shown correspond to the N-S component. The spectrogram corresponds to the unfiltered data and was calculated using a window length of 1800s.

The passage of cold fronts results in changes in atmospheric pressure that can be detected by seismic stations, as the change in density of the atmosphere above the instrument modifies the Newtonian attraction of the sensor mass¹². Figure 2a shows the signals related to atmospheric waves generated by the Hunga-Tonga eruption as recorded in the seismic station CAVN, part of the CA network¹³ and located in NE Iberia, at about 17,600 km from the volcano. Although the signals can be identified in the three components of the seismic records, their amplitude is greater in the north-south oriented component, as this is the relative orientation between Tonga and NE Iberia. The spectrogram shows two arrivals about 4 hours apart, with spectral content restricted to the 1–3 mHz range (orange dashed lines in Fig. 2a). These arrivals correspond to Lamb waves that have travelled following the two directions of the great circle between the point of origin and the place of registration. Overprinting the first Lamb wave, the spectrogram shows the arrival of a wave with a strong dispersive character, with frequencies around 1 mHz arriving a few minutes after the Lamb wave and frequencies around 40 mHz arriving 45 minutes later (red dashed line in Fig. 2a). Wright et al.¹⁴ have shown the existence of gravity waves with continuously varying speeds that could correspond to our observations, although further modelling will be needed to assess this point. The dispersive wave corresponding to the long

pathway is not observed, probably due to the effects of attenuation. The arrival of two atmospheric waves with differentiated spectral properties is observed in a large number of the stations analyzed.

Analysis of the extended time recordings up to 5 days (Fig. 2b) reveal further features. Seismic waves from the main blast arrive at this station 20 minutes after the time of origin (blue dashed line), while atmospheric waves propagating along the shortest path between Tonga and Iberia arrive 16 hours later. After large earthquakes, it is common to record multiple global circling waves, separated by intervals of close to 3 hours. In this case, what is recorded seismically is the passage of a Lamb wave travelling at near acoustic speed and therefore taking around 36 hours to circumnavigate the planet. Clear signals around 10:00 on the 17 January and an additional one around 22:00 on the 18 January (Fig. 2b) are easily identified. This highlights the enormous energy generated by the main explosion, which has allowed its seismic detection after propagating for more than 100,000 km during three and a half days. No dispersion is observed for the second and third passages of the atmospheric wave, suggesting that in these cases the recorded energy corresponds to a pure Lamb wave.

Although not all surveyed stations clearly show these arrivals, we have found that it is a fairly common observation. A four-day

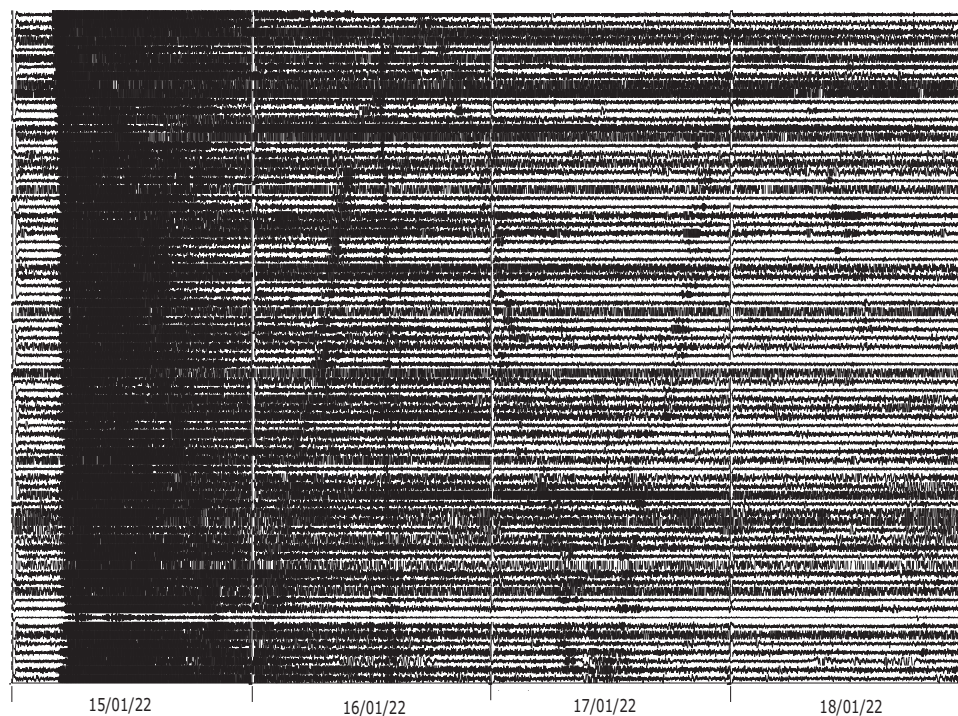


Fig. 3 Seismic record of the successive passages of the atmospheric Lamb wave in stations distributed throughout the planet. The data have been band-pass filtered between 0.5 and 5 mHz, classified according to their distance from Hunga-Tonga and represented without amplitude normalization.

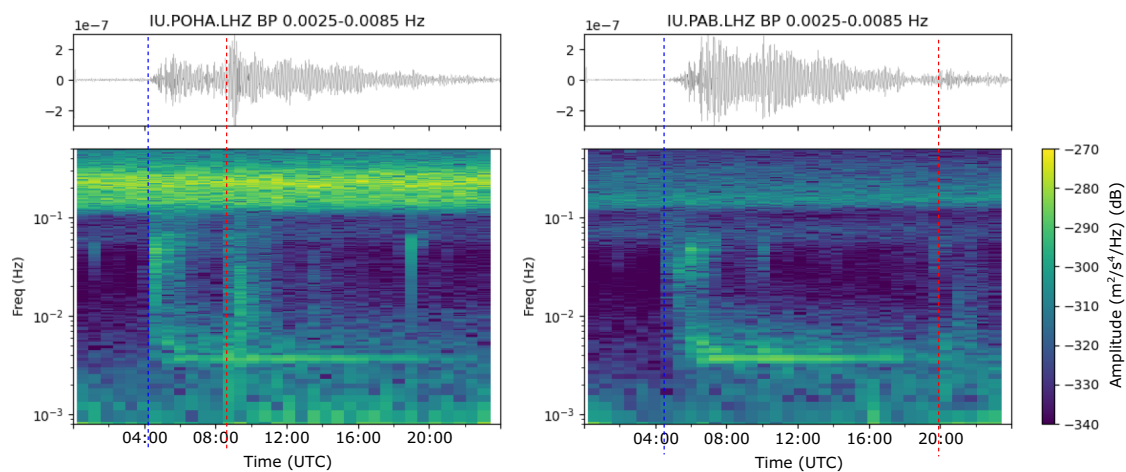


Fig. 4 Examples of the low-frequency near-monochromatic signals detected following the eruption. Seismic traces and spectrograms for two representative sites; IU.POHA station, located in Hawaii (distance: 4955 km), and IU.PAB, located in central Spain (distance: 17,730 km). The traces have been corrected for the instrument response and filtered between 2.5 and 6.5 mHz. Amplitudes are expressed in m/s. Blue dashed lines show the onset of the low-frequency signal, while red dashed lines show the arrival of the Lamb waves.

long representation of low-frequency seismic data (Fig. 3) reveal multiple passages of the Lamb wave, with stations located far from the source and its antipodal point detecting up to five Lamb wave passages. To our knowledge, there are no previous observations of this kind of long-lived atmospheric-ground coupling.

Low-frequency near-monochromatic signals. Figure 4 shows the seismic trace and the corresponding spectrogram for two stations located at different epicentral distances, POHA (Pohakuloa, Hawaii), at 4955 km, and PAB (San Pablo, central Spain) at 17,735 km. In both cases, the arrival of the seismic waves generated by the volcanic explosion is shown with blue dashed lines.

Red dashed lines show the Lamb waves, which reach POHA around 8:30 and PAB around 20:00. The most prominent feature of the spectrograms is the high energy detected around 3 mHz, lasting 10–12 hours.

This low-frequency, long-duration signal appears clearly in a seismic section similar to the one presented in Fig. 1, but now filtering between 2.5 and 6.5 mHz (Fig. 5a). The first observations of this kind of signals date back to the early 1990s, following the eruption of Mount Pinatubo in 1991^{15,16}. The signals were described as bichromatic, with two spectral peaks at 3.7 and 4.3 mHz. Inspecting previous data, Widmer and Zürn¹⁶ identified similar signals produced by the 1982 El Chichón eruption, with spectral peaks located in this case at 3.7 and 5.1 mHz. No further

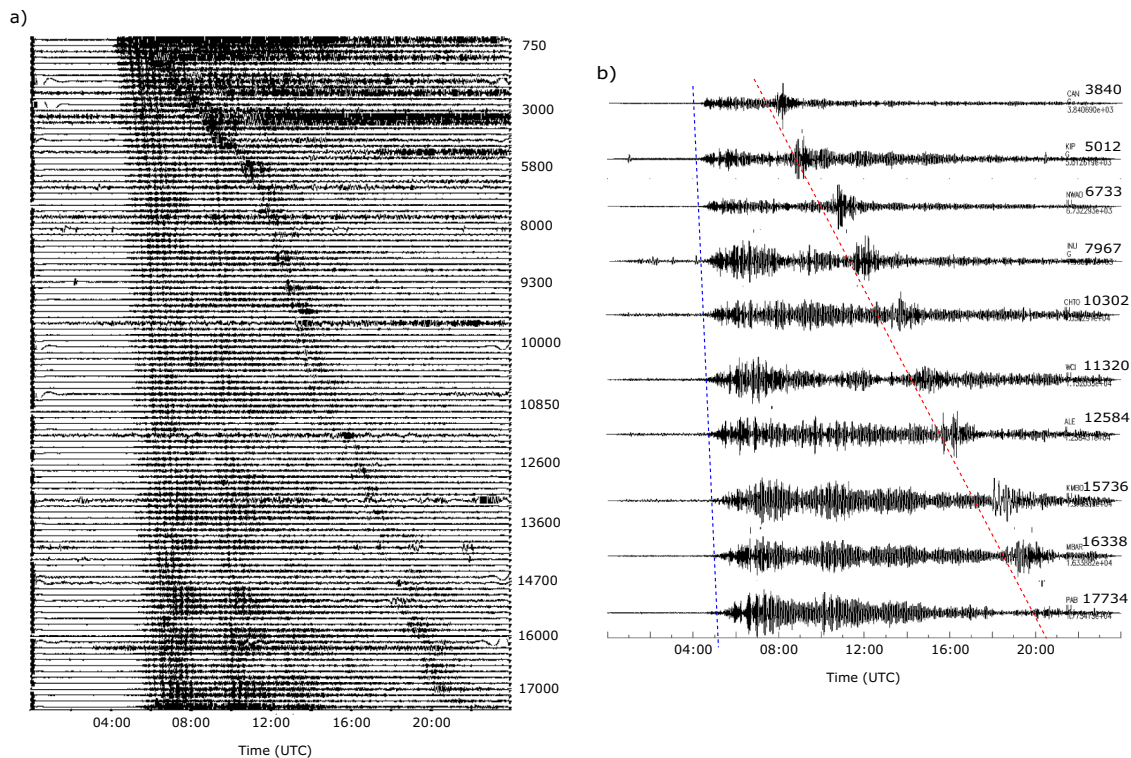


Fig. 5 Low-frequency and atmospheric Lamb wave arrivals around the world. **a** Seismic traces for the entire dataset filtered between 2.5 and 6.5 mHz. The instrument response has been removed and the traces are not normalized in amplitude. Labels show the distance to the Hunga-Tonga volcano (in km). **b** Selected traces at different distance ranges, filtered in the same frequency band. Blue dashed line marks the onset of the low-frequency signal and red dashed lines mark the arrival of the atmospheric Lamb waves.

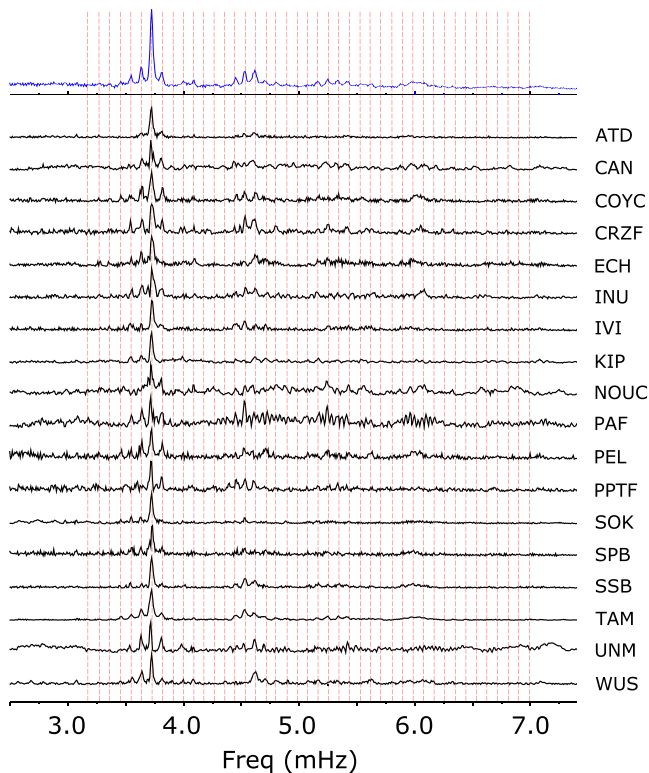


Fig. 6 Normalized amplitude spectra for a selection of seismic stations. The spectra has been calculated for the 24 hours of the day of the eruption using stations of the Geoscope network distributed throughout the world. Blue line shows the spectra stack of the 95 traces analyzed. Red dashed lines show the eigenfrequencies for the PREM model.

evidence of low-frequency seismic signals observed worldwide has been reported since then.

To better explore the properties of these signals, we have calculated the spectra of each seismic station using a 24-hour interval. The spectra obtained for a selection of sites gives evidence for the presence of clearly defined amplitude peaks between 3 and 6 mHz (Fig. 6). As the frequency and relative amplitude of these peaks are rather constant, we have stacked the results obtained from the 95 available stations to produce the stacked spectra shown as a blue line. The regular spacing of the peaks suggest that they may be related to the spheroidal normal modes of the Earth that form the so-called “Earth’s Hum”. To verify this point we have added to the figure the eigenfrequencies of the Earth, calculated from the PREM Earth reference model¹⁷, as reproduced in Tanimoto et al.¹⁸. As clearly shown, the dominant frequency is 3.7 mHz and corresponds to the oS_{29} spheroidal mode. A second group of spectral peaks with high energy is seen around 4.65 mHz. Moving to higher frequencies, a third group can be identified around 5.4 mHz and a last one around 6.0 mHz. It is interesting to note that for each of these groups, the modes around the dominant one also have large energy.

Kanamori and Mori¹⁵ and Widmer and Zürn¹⁶ interpreted the two spectral peaks observed in their data as resulting from two atmospheric waves, the low-frequency one being a gravity wave and the other a pressure wave. Widmer and Zürn¹⁶ pointed out a feedback regime between the atmosphere and the volcano and attributes the difference in the high frequency value between El Chichón and Mount Pinatubo (5.1 vs 4.4 mHz) to temperature changes in the atmosphere affecting the pressure wave. Following a different approach, Lognonné et al.¹⁹ considered the solid Earth and the atmosphere as a single system and calculated the theoretical normal modes, concluding that the 3.7 and 4.4 mHz

modes are the ones with the highest energy in the atmosphere. Using these theoretical modes, Lognonné²⁰ built synthetic seismograms that fit the signals from Mount Pinatubo with a source located at 24–28 km of altitude and showed, as in our dataset, a relevant increase in amplitude near the antipodal point. Therefore, it seems reasonable to expect that future work following this approach will be able to model the spectra using a synthetic model. At local scale, Dautermann et al.²¹ reported borehole strainmeters and GPS-TEC signals with a maximum amplitude of around 4 mHz following the collapse of the Soufrière Hills lava dome (Montserrat, Lesser Antilles) in July 2003. These signals were interpreted as resulting from the superposition of atmospheric modes triggering resonant coupling with the solid Earth at 4 mHz. In a recent contribution, Yamazaki et al.²² have reported a geomagnetic oscillation following the Hunga-Tonga eruption, with a dominant frequency of 3.8 mHz, detected at magnetic conjugate points and interpreted also as due to the atmosphere acoustic resonance.

The spectra stack constructed using 95 stations distributed around the world shows that the signal cannot be described as bichromatic, as there is a clearly dominant mode group around 3.7 mHz, but also three other mode groups with relatively high amplitudes, with maximums at 4.5, 5.3 and 6.0 mHz. For all four groups, the main mode has peaks of lower amplitude on both sides and that all of them coincide with the eigenfrequencies of the PREM Earth reference model. Thus, we favour an origin related to a coupling of the atmospheric system-solid Earth, in which the large atmospheric explosion resulted in the excitation of the normal modes of the Earth between 2 and 6 mHz, the so-called “Earth’s Hum”, with higher amplitudes at frequencies where atmospheric waves carry more energy and can be better transferred to the ground.

As seen in Fig. 5b, at stations located at large epicentral distances, the amplitude of the low-frequency signal decreases smoothly with time, only to increase again between 09:00 and 10:00 UTC. The timing of this increase coincides with the arrival of surface seismic waves generated by the 08:30 volcanic explosion (see Section 2), which suggests that this event may have increased the level of normal mode excitation.

Conclusions

Analyses of seismic data collected by networks on a global scale have provided new information regarding the temporal evolution of the Hunga-Tonga eruption, confirming that the three umbrella clouds identified in the satellite data at 04:00, 05:30 and 08:25 are associated with strong explosions that have generated seismic waves propagated on a global scale. The main eruption started a few minutes before the time indicated in the seismic catalogues and had a complex low-frequency waveform, with a first VLP pulse repeated up to three times during the first four minutes of signal, hence evidencing an episodically repeated volcanic source. Very similar VLP can be identified at the signals produced by the two later events, proving that the source mechanism has remained active during several hours.

The atmospheric Lamb wave generated by the main explosion has been detected in seismometers during 3 and a half days, with many sensors detecting up to five passages of the wave, hence giving evidence for the exceptional energy liberated by the Hunga-Tonga explosion. During the first passage, many seismic stations show the arrival of a second atmospheric wave, of a dispersive nature, that moves with a slightly lower speed, which could correspond to a gravity or pressure wave.

The low-frequency and long-duration signals identified in this episode had only been previously described as a consequence of the 1982 El Chichón and 1991 Mount Pinatubo volcanic

eruptions, and should be considered exceptional. Observed at a large number of sites distributed around the world, these signals are attributed to the excitation of the Earth’s normal modes as a consequence of the main volcanic explosion. Considering that the normal mode with more energy is 3.7 mHz, we can say that the Earth has been beating every 4.5 minutes during the hours following the powerful Hunga-Tonga explosion.

Methods

To inspect the seismic data at global scale, we have selected a group of broad-band seismic stations integrated in the main worldwide-scale seismic networks, including the Global Seismograph Network²³, the IRIS/IDA seismic network²⁴, Geoscope²⁵ and Geofon²⁶. We have downloaded and processed the available data, restricting ourselves to the LHZ channels, with a sampling rate of 1 sample per second. In addition, we have inspected data from the broad-band seismic networks covering SW Europe, including the FR²⁷, ES²⁸ and CA¹³ networks to check eventual regional scale variations in an area not far from the antipodal position with respect to the eruptive zone.

The instrument response has been removed from the data using the standard procedures included in the Obspy package²⁹.

Spectra and spectrograms have been calculated using SAC³⁰ and Obspy²⁹ routines using standard parametrizations.

Data availability

All the seismic data used in this contribution are publicly available using the ORFEUS EIDA (<http://www.orfeus-eu.org/data/eida/>) and FDSN (<https://www.fdsn.org/services/>) data services. The code and DOIs of the seismic networks used are: CA, <https://doi.org/10.7914/SN/CA>; IU, <https://doi.org/10.7914/SN/IU>; II, <https://doi.org/10.7914/SN/II>; G, <https://doi.org/10.18715/GEOSCOPE.G>; GE, <https://doi.org/10.14470/TR560404>; FR, <https://doi.org/10.15778/RESIF.FR>; ES, <https://doi.org/10.7914/SN/ES>

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Competing interests

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Additional information

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