Nat. Hazards Earth Syst. Sci. Discuss., author comment AC2
https://doi.org/10.5194/nhess-2022-200-AC2, 2022

Reply on RC2

Gui Hu et al.

Author comment on "The characteristics of the 2022 Tonga volcanic tsunami in the Pacific Ocean" by Gui Hu et al., Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2022-200-AC2, 2022

Response to referee #2 for NHESS manuscript nhess-2022-200 by Hu et al

Note: The comments are in "*italics*", and our responses are in "regular" text (in blue) for clarity.

General Comments:

In this study, authors conducted wavelet analyses to investigate the characteristics of the 2022 Tonga volcanic tsunami, which is, to date, the most important event in the geoscience field in 2022. The MS presents some interesting results. Nevertheless, there are still many flaws, which need to be further polished, clarified, and validated with deep and serious thinking. My comments include,

Author's response☐We are very grateful to referee #2 for the detailed advices and comments which definitely are very helpful in improving the clarity and rigor of this manuscript. Here, we present our point-by-point responses and revision to each of the comments.

Author's change to manuscript☐Please see the detailed changes in our response to each comment.

1.Line 21, Lamb wave with ~30-40 min period? So long?

Author's response: The Lamb wave is well studied as the signature is clear and conspicuous in both sea surface and atmosphere. Its velocity of ~300-340 m/s is distinctly different from that of gravity waves of ~200-220 m/s (Kubota et al., 2022) and shock waves of ~1000 m/s. Therefore, we can well identify the arrival of Lamb wave from the waveforms recorded by DARTs and barometers. By carefully analyzing their wavelet, we find the period of Lamb wave is ~30–40 min. The 30-40 min period is consistent with the dominant periods 1700–2500 s (28.3–41.6 min) identified by Matoza et al., 2022 who did the analysis of a mass of barometric and seismic data. The period is also similar with the Lamb wave period of 2000 s (33.3 min) detected by 25 comprehensive infrasound sensors installed along the coastline of Japan with wider frequency range than conventional barometers (Nishikawa et al., 2022). Such a long period is probably excited by the long-duration climactic eruption (Matoza et al., 2022).

2.Lines 107-108, Why using cut-off frequency of ~8 hr could remove the tidal components? There are various tidal components.

Author’s response: The dominant periods of astronomical tides are generally ~10 hr. The subperiods (Power relation of 0.5 with the dominant period) of the tide are not significant compared with the dominant one and can be mixed with the excited nontidal oscillation periods (Parker, 2007). For example, in shallow waterways, nontidal phenomena such as river flow and low-frequency storm surge can affect the amplitudes and phases of some tides. In the case, we use the cut-off frequency of ~8 hr to keep as much as tsunami information and meanwhile remove the dominant tide components. This frequency has been successfully applied to many tsunami cases. For example, it works well on tsunamis generated by the 2011 Mw 9.0 Tohoku megathrust earthquake (Heidarzadeh & Satake, 2013) and the 2022 Mw 6.9 normal-faulting intraplate earthquake (Doğan et al., 2021).

3.Line 110, Why ignore such small tsunami height data?

Author’s response: We explain that we only delete the tidal gauge stations with the maximum tsunami height less than 0.2 m. All the DART stations remain as tsunami waves in deep ocean possess very small wave amplitudes. The reasons we apply this step to tide gauge data are: First, the gauges distributed along different locations in the Pacific coastline possess different scales of noise signal. To minimize the effect of the noise on the waveform analysis, we ignore stations whose tsunami height is close to that of noise signal. Second, data from the remaining tide stations are sufficient to demonstrate our key points.

Author’s change to manuscript□For clarity, we’ve rephrased the sentence as : ‘…with the maximum tsunami heights of tide gauges less than 0.2 m…’.

4.Please specify the azi definition in the figure caption, specify the unit of distance. Please also add the magnitude of the ordinate to quantitatively specify the sea level.

Author’s response□We’ve modified the part about “azi and distance unit” accordingly. The heights of the stations are distributed within a wide range from ~3 m to 0.2 m. To clearly demonstrate the data with such a wide range, we choose to normalize the data instead of using the raw data. That’s the reason we didn’t put a scale in the figure. The previous ordinate is misleading. We’ve corrected the label of the ordinate.

Author’s change to manuscript□We’ve added the units in the figure and a sentence to specify the Azi definition in the caption as: “Azi stands for azimuth”. We’ve corrected the “sea level (m)” with “Normalized wave amplitude”.

5.Line 134, Why Gaussian-shaped initial sea level displacement is used? Can it mimic the volcano eruption induced gravity wave propagation?

Author’s response□The main purpose of using Gaussian-shaped point source is to calculate the theoretical arrival times of conventional tsunami generated by seafloor crustal displacement. The Gaussian-shaped point source probably cannot realistically mimic the volcano eruption induced gravity wave propagation, but the arrival times are not very sensitive to the source property in this specific case.

6.Line 144, Why Morlet mother function is selected?

Author’s response□Morlet wavelets have several advantages for time-frequency analysis. First, it is Gaussian-shaped in the frequency domain. The absence of sharp edges minimizes ripple effects. Second, wavelet convolution is more computationally efficient, because most of which are implemented with the fast Fourier transform. Third, the convolution result can retain the temporal resolution of the used signal (Cohen, 2018).

7.Line 149, Why moving time window is selected as 20 min?

Author’s response□We use moving time window in the Averaged-Root-Mean-Square (ARMS) method to measure the absolute average tsunami amplitude in the window for coastal tide gauge. To achieve this purpose, we need to choose a representative wave period that covers most tsunami waves with significant amplitude and long-lasting time duration, as the moving time window. With the criterion, we exclude the periods of tsunami components from shock wave, Lamb wave and conventional seafloor crustal displacement, because they are either distributed in a limited time period in each waveform, or have very limited spatial and temporal impact, therefore, do not meet the requirements. Specifically, significant shock wave and Lamb wave are mainly concentrated in the narrow time periods of their arrivals. Conventional tsunami is only observed in the proximity of the eruption site. Only tsunami component from the air-sea coupling with atmospheric gravity wave possesses significant waveform for a long time and the wave period band of such coupled waves is ~10-30 mins. Therefore, we choose 20 min as the moving time window. Base on our test, an alternative time window in the range of 10-30 min can also get the similar duration result.

8.Lines 163-164, This could not be observed in Fig. 1. Please specify the theoretical (gravity wave) tsunami speed in Fig. 1 to show that Lamb wave is faster.

Author’s response□Thanks, done as suggested.

9.Lines 164-165, Why Fig. 2 could not detect the Lamb wave related tsunami signals?

Author’s response□Lamb waves is clear in waveforms recorded by DARTs (the left column) because DARTs deployed in deep ocean capture clear Lamb waves. However, tsunami left by each passage of the atmospheric waves in tide gauges (right column) is much affected and amplified by the complicated coastlines and local bathymetric features, which render the lamb wave not that conspicuous in tide stations, so it’s harder to see clearly outstanding Lamb wave signatures in the coastal gauges.

10.Line 165, Lamb, L should be capital. Please double check this throughout the entire MS.

Author’s response□Thanks, done as suggested.

11.Lines 168-169, Why such definition? In data pretreatment, data with the maximum tsunami height less than 0.2 m have been deleted? Nevertheless, a very small value of 0.1 mm (could be recording error in many data) is considered here?

Author’s response□The definition is based on our tests, in which 0.1 mm can well represent the amplitude of Lamb wave arrivals, so the time points at which the tsunami amplitudes first exceed 0.1 mm above sea level are defined as Lamb wave arrivals. About the usage of 0.2 m, we only delete the tidal gauge stations with the maximum tsunami height less than 0.2 m. All the DART stations remain as tsunami waves in deep ocean possess very small wave amplitudes.

12.Line 178, In Eq. 2, temperature is for low elevation or high elevation? If low, then moving towards North Pole is accompanied with the decease of temperature, thus the decreased Lamb wave speed. However, if it is temperature at high elevation, the above explanation fails.

Author's response☐The equation is built on an assumption of an isothermal troposphere, the phase velocity is only affected by the air temperature. DARTs we use measure the sea surface elevation in deep ocean, so the temperatures we obtain are for low elevation. The equation has been successfully applied in numerical simulation of atmospheric Lamb waves of 2022 Tonga eruption (Amores et al., 2022).

13.Line 181, CL, L should be subscript.

Author's response☐Thanks, done as suggested.

14.How the black lines are obtained? They are very much sensitive. Please add wave height elevation information in Fig. 3.

Author's response☐The black lines represent different constant velocities (in Fig. 3). We set the velocity to fit the Lamb wave arrival, in order to obtain the spatial variation in Lamb wave velocities. The waveforms are normalized instead of using the raw data, so it's may be confusing to add elevation information.

15.Line 196, Can not confirm the complex geometries of the coastlines in Fig. 4a.

Author's response☐Thanks. We have added a figure of the coastlines of Japan in the supplementary as a representative, to present the complex geometries of the coastlines.

16.Line 198, Can not see the bay shape in Chanaral.

Author's response☐We have added a figure of the bay in Chanaral in the supplementary, to present the bay shape in Chanaral.

17.Lines 206-207, Why interaction between tsunami and bathymetry could delay the arrival of maximum tsunamis? There are always interactions between bathymetry and tsunami propagation. It is inherent.

Author's response☐Tsunami interaction with different bathymetry features can lead to various effect. Some bathymetric effect can delay the arrival of maximum tsunamis. For example, the edge waves (Satake et al., 2020) and resonance effect (Wang et al., 2021) from tsunami interaction with different local bathymetry can produce late maximum tsunami amplitude (Satake et al., 2020). The interaction phenomenon between tsunami and bathymetry is better understood for conventional tsunami originated from seafloor crustal displacements, but it's not well studied for atmospheric tsunami from volcanic eruption as it's so rare and complicated. So, we feel it's necessary to emphasize the idea here. To make the delayed cause more clear, we added the specific phenomenon in the main context.

Author's change to manuscript☐We added a sentence in the related context: "For example, the delayed maximum tsunami height can be attributed to the edge waves (Satake et al., 2020) and resonance effect (Wang et al., 2021) from tsunami interplays with bays/harbors, islands, and continental shelves of various sizes."

18.Lines 211-214, Why the first waves in DART are supposed to be the maximum? The first wave is induced by the Lamb wave, it is small (should be only about 2 cm corresponding to 2 hPa), whereas the maximum waves should come from other mechanisms.

Author's response☐Since the DART stations are located in the deep ocean, the contribution from shoaling effect and interaction with complex coastlines is relatively limited. Based on previous observations (e.g. Heidarzadeh & Satake, 2013), the first tsunami waves are normally the largest waves at most DART stations. The delayed maximum waves suggest other mechanism might have contributed to the tsunami case, which has been proven to be atmospheric gravity waves.

19.Lines 233-234, Why not in sequence? These bands cover almost all time period in Fig. 5.

Author's response□Thanks, we have corrected the sequence.

Author's change to manuscript□We've rephrased the sentence as: "… 3–5 min, 10–30 min, 30–40 min, and ~80–100 min …"

20.Lines 234-235, Please be specified.

Author's response□Thanks, done as suggested.

Author's change to manuscript□We've rephrased the sentence as: "2) The significant tsunami component with period band of 3-5 mins are recorded by stations between the eruption site and the north tip of the New Zealand."

21.Lines 235-236, Please be specified.

Author's response□Thanks, done as suggested.

Author's change to manuscript□We've rephrased the sentence as: "3) There exist one exceptional tsunami component with longer wave period of ~80–100 min mainly recorded in the Tonga, the New Zealand and Hawaii, which travels even faster than the lamb waves."

22.Lines 256-260, No need since these have be specified in the figure caption.

Author's response□Thanks, removed as suggested.

23.Line 263, There is no Hawaii in Fig. 5. In fact, the 80-100 min wave energy in these two regions on the left of the vertical white line is rather small, and no clear difference from other points.

Author's response□We've added Hawaii station in the sentence. The 80-100 min wave energy is supposed to be around the vertical white lines instead of on the left of the lines. As all stations in Fig. 5 are located in New Zealand, close to the eruption site, the energy of the tsunami components occurs at the similar time and couple together, which therefore may be little hard to distinguish for some stations (such as NZG, NZF and NZJ). The small energy of the 80-100 min wave distributed in the stations NZG, NZF and NZJ could also attribute to the complicated air-sea coupling conditions, which is poorly understood because of limited observation. However, Fig. 7 shows that the clear and consistency of the component are recorded by barometers in New Zealand.

Author's change to manuscript□We have modified the text as : …e.g., stations 52406, NZJ, NZE, 51425 in Figure 5, and 51407 in Fig. 6

24.why the signals are filtered between 30 min and 150 min, whereas the period band is ~80-100 min in line 261. Why different?

Author's response□To clearly show the ~80–100 min wave component which arrives prior to Lamb wave in figure7, we have to keep Lamb wave period component as a reference so we start from 30 min (lower period limit of the Lamb wave). ~80–100 min is a general period band of the tsunami component, not an exact value. Periods of some tsunami components are longer than 100 min. To keep as much as period information of various tsunami components, we choose 150 min as the upper period limit. According to our tests, changing the upper period to 130 min or 140 min does not affect the results.

25.Lines 269-272, Hard to identify this in Fig. 7. There are no clear difference between the left and right two columns regarding the signals around the vertical solid green line.

Author's response☐Indeed, the signals are not visually conspicuous as the Lamb waves. But they are relatively well detected by the wavelet analysis of waveforms recorded by both DARTs and barometers in New Zealand. And compared with background noise signal prior to Lamb wave, the waveforms of the stations in New Zealand (For example, WhauVaully, 39944, 12442, 44556, 44761) have more clear amplitudes at the green lines than those in the rest of station in the Pacific Ocean.

26.Lines 285-286, The large energy of the air pressure of 10-30 min band in Fig. 8 only appears around the arrival of Lamb wave, while large energy of tsunami wave of 10-30 min band shows a much longer duration in the volcano near field in Fig. 5 (after the arrival of Lamb wave), and a relatively short duration in the volcano far field in Fig. 6 (after the arrival of Lamb wave). I do not think Figs. 5, 6 and 8 are consistent with respect to this point. Appreciate if authors could further dig out the physical insights behind.

Author's response☐Thanks for raising such interesting question which encourage us to explore further of our results. By careful checking the original waveform data, we realize the duration variability shown in different DARTs is actually related to the duration of event mode set by each DART station. Passing tsunami waves trigger the DART system to enter event mode (with sampling rate of 15 seconds or 1 min) from normal frequency mode (15 min time interval) (www.ndbc.noaa.gov/dart). When the tsunami signals eventually die down, the recording frequency will be switched back to normal mode. The 10-30 min tsunami component can be well detected by the sampling rate of 15 second or 1 min, but not by the rate of 15 min. Therefore, we see different durations of 10-30 min band in Figures 5 and 6.

27.The colorbar seems strange. It should represent the energy. Why negative values? what is the meaning of dB? As for the left and right ordinates of each sub-figure, their scales are different, left around 10^3, while right around 10^1. Why? As for the wavelet results, why there is no blanked-out peripheral area of the spectrum, i.e., 'cone of influence', the portion of the spectrum sensitive to the end-effects. These areas should be blanked where results may be artificially affected. Similar problems for the entire wavelet analyses.

Author's response☐dB is a unit to measure the relative magnitude of energy. The method is proposed by ALEXANDER B. RABINOVICH, and detailed description of the method can be found in (Rabinovich, 2009). We use different units on the left and right ordinates of each sub-figure, i.e. second and minute respectively, to presnt the results in different unit ordinates. We conduct wavelet analysis for longer original waveform and wider period band than presented, to avoid blanked-out peripheral area.

28.How Eq. 4 is obtained?

Author's response☐Thanks, we've added a citation (Rabinovich, 1997) to explain the equation, through which you can find the detailed derivation of this equation.

29.Lines 361-362, How are these factors specified from the present study?

Author's response☐The influence conditions are mentioned in the second paragraph in section 4.1. We paste the related part here: "The long-traveling capability could be associated with the ~ 10000 m deep water depth of the Tonga Trench that keeps the source signals from substantial attenuation. In deep open ocean, the wavelength of a tsunami can reach two hundred kilometers, but the height of the tsunami may be only a few centimeters. Tsunami waves in the deep ocean can travel thousands of kilometers at high speeds, meanwhile losing very little energy in the process. The long oscillation can be attributed to the multiple reflections of the incoming waves trapped in the shallow-water bay at Charleston."

30.10b, atmospheric and tsunami wave forms are also not mentioned in the context, these sub-figures could be deleted.

Author's response□Fig. 10b is mentioned in the second paragraph in section 4.2.

31.Lines 374-378, Lamb wave speed is rather fast, even it circles the earth multiple times, it should not or less contribute to the 3 days tsunami event, especially considering that after circling, the Lamb wave energy decays.

Author's response□Yes, we agree with your opinion which is also suggested by our results.

32.Line 379, what is the meaning of resonance between ocean and atmospheric waves? They have very much different frequency, how can resonance between these two be triggered?

Author's response□Some atmospheric gravity wave modes have velocities close to that of tsunami waves in most parts of the Pacific Ocean, which results in resonance effect (Kubota et al., 2022).

33.Line 380, What is the difference among atmospheric gravity wave, Lamb wave, and shock wave? These concepts must be clarified in the context.

Author's response□Thanks, we have added explanations in the Introduction section to clarify the concepts.

Author's change to manuscript□The added sentences in the Introduction section: "Atmospheric waves propagating in the atmospheric fluid with different speeds are generated by different physical mechanisms (E. E. Gossard & W. H. Hooke, 1975). Nonlinearities in the process may lead to the formation of shock-wave and period lengthening. The balance between gravity and buoyancy causes gravity waves. The acoustic wave propagate by atmospheric fluid compression and rarefaction (Matoza et al., 2022)."

34.Line 385, Please specify what kind of tsunami speed here mentioned?

Author's response□ To make the logic of this part smoother, we've modified the context. We first explain the definition of Proudman effect and then mention the tsunami speeds more specifically.

Author's change to manuscript□We've modified the related text as: "Second, when Lamb wave speed approaches the tsunami speed, Proudman resonance gradually increase tsunami heights, wherein Proudman resonance optimally maximizes tsunami heights when they match well. In deep oceanic trenches, such as Mariana and Tonga-Kermadec trench (10000–11000 m), tsunami velocities range between ~314–330m/s which are comparable with those of the observed Lamb waves 315–340 m/s."

35.Line 387, Proudman resonance is a well-known and old concept. No need to refer 2022 papers. Why continuously? the deep trench is generally rather narrow, while the Lamb wave speed is very fast and it only need short duration for Lamb wave passing through the trench.

Author's response□Thanks, we've removed the word 'continuously' as suggested and put the citations of the 2022 papers in a more appropriate place. The explanation of possible contribution of the Proudman effect is largely based on its theoretical definition. Since in some of the deep oceanic trenches, tsunami velocity could range between ~314–330m/s which are comparable with that of the observed Lamb waves 315–340 m/s, we can't exclude its contribution to the tsunami oscillation, theoretically.

Author's change to manuscript□We've rephrased the sentence as: "Therefore, the resonance effect could be a possible source of increased wave energy, especially in the deep trenches (Lynett et al., 2022; Tanioka et al., 2022)."

36.Lines 393-394, Why a 2005 paper is referred for the 2021 Tonga event??

Author's response□Thanks for pointing out this mistake. We have replaced the reference with a corrected one.

Author's change to manuscript□"…fast-moving atmospheric waves for the Mw 5.8 volcanic eruption (Matoza et al., 2022) …"

37.Line 396, only 70 km from the source??

Author's response□The maximum runup of the 2011 Tohoku earthquake is measured at Miyako in the Iwate Prefecture, a coastal port ~70 km away from the epicenter.

38.Line 429-430, Resonance effect can only amplify the tsunami height, no the duration. The description here is not serious.

Author's response□Thanks for pointing out the unserious description. We've changed our description here.

Author's change to manuscript□" we do not have clear evidence that atmospheric acoustic-gravity waves from the 2022 HTHH eruption directly contribute to the long-lasting tsunami, but the resonance effect associated with ocean waves could a possible source of increased wave energy."

39.Lines 433-435, Fig. 11 indicate that the long-lasting of HTHH tsunami is not related to the Lamb wave induced tsunamis, but related to the subsequently gravity wave and its interaction with the coastal bathymetry and coastal configuration. In other words, interactions between the Lamb wave induced tsunamis and coastal bathymetry/coastal configuration are negligible.

Author's response□Thanks. Based on our analysis, we think the long tsunami duration is indirectly from the contribution of air-sea coupling with atmospheric acoustic-gravity waves (including shock wave, Lamb wave, gravity wave), but the interaction of local bathymetric characteristics with the ocean waves left by each passage of atmospheric acoustic-gravity waves. The comparison of hydrodynamic characteristics between the 2022 HTHH tsunami event and the 2011 Tohoku tsunami event suggests the volcanic tsunami oscillation was prolonged by their interplays with local bathymetry.

40.Please specify the meanings of different white dashed lines in Fig. 11 caption.

Author’s response☐Thanks, done as suggested.

Author’s change to manuscript☐We’ve added a sentence as: “Horizontal white dashed lines respectively mark reference periods of 10 min and 30 min. “

41.Lines 454-455, Generally, I do not think Proudman resonance from the Lamb wave is the reason for the large coastal tsunami height since the ocean is still too shallow and the deep trench only exists within a narrow area being generally perpendicular to the tsunami propagation direction.

Author’s response☐Thanks. We agree that Proudman resonance from the Lamb wave is not the reason for the large coastal tsunami height. Regarding the contribution of Proudman resonance to the tsunami event, please kindly refer to our response to comment 35.

42.Lines 456-463, There have been well-known from the previous studies. The trapping effect in the coastal region should be considered for tsunami warning, e.g., edge wave and so on. The resonance effect can only amplify the tsunami wave height, which may indirectly leads to the long lasting of tsunami event.

Author’s response☐Thanks. When the oscillation periods of ocean wave and local bathymetry (bays/ harbors or the continental shelves) match, the resonance effect between ocean waves and local bathymetry form. The effect can not only amplify the tsunami height, but also prolong the tsunami duration (Satake et al., 2020;Wang et al., 2021). The long duration is produced by the reflection and interference of tsunami waves at the edge of bays/ harbors or the continental shelves. For example, following the main tsunami arrival, a series of waves reflect from the shelf edge back to the coast repeatedly. These repeated reflections not only trap the tsunami energy from entering the deep ocean, but also constitute shelf resonance (Rabinovich, 2009). Similarly, in harbor/bay case, incident waves reflect back from the end of the bay and reach the entrance repeatedly(Miles, 1974). Such reflections prolong the duration of tsunami events.

43.Conclusions should be amended following the aforementioned comments.

Author’s response☐Thanks, we have revised the manuscript accordingly.

Author’s change to manuscript☐We’ve modified the related context in the conclusion: “Although the resonance effect with the atmospheric acoustic-gravity waves theoretically could be a source of increased wave energy, its direct contribution to the long-lasting oscillation is not demonstrated yet. However, the comparison of hydrodynamical characteristics between the 2022 HTHH tsunami event and the 2011 Tohoku tsunami event well demonstrated that the interactions between the ocean waves left by atmospheric waves and local bathymetry contribute to the long-lasting Pacific oscillation of the 2022 tsunami event.”

Reference

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