briefing note **460** Jan 2022

Why the Tonga tsunami arrived much earlier and much larger than expected

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Introduction

Tsunamis are surface water gravity waves originating from the sudden displacement of water occurring in an earthquake, volcanic crater collapse, or underwater landslide. The local propagation speed of tsunamis is given by the square root of g.H, where g is the acceleration of gravity and H is the local water depth. As the water depth of the oceans is well known from bathymetry, it is straightforward to calculate the arrival times of tsunami. The calculated travel times for the Tonga tsunami, assuming an earthquake source, are shown on the left side of Figure 1.

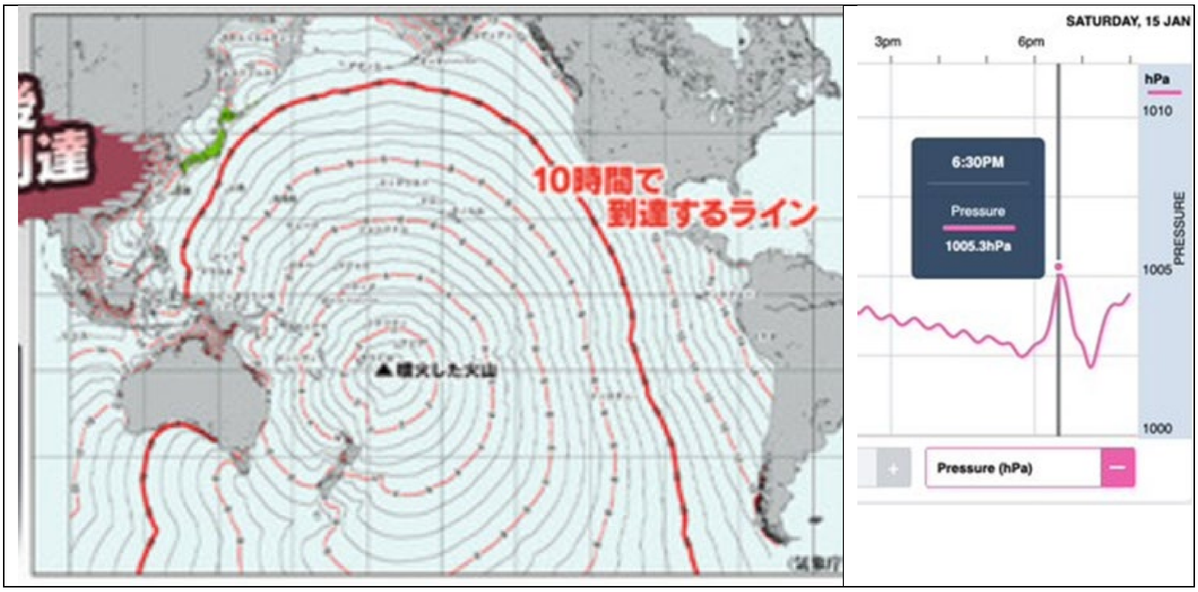
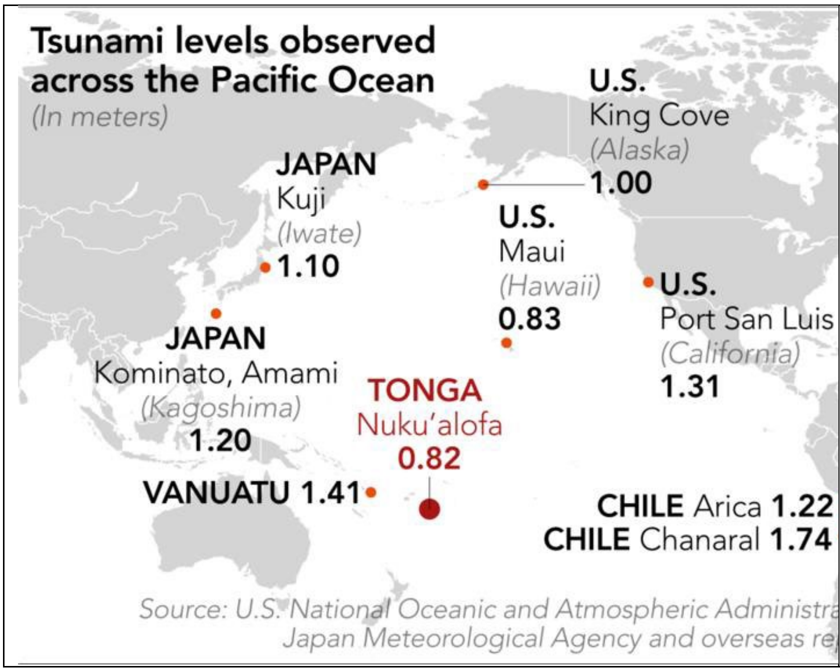


Figure 1*. Left: Predicted tsunami travel times throughout the Pacific Ocean for an earthquake generated tsunami. The red contours are 2 hours apart and the black contours are 30 minutes apart. Source: Watada (2022). Right: Arrival of the air pressure wave in Sydney at 6 pm. Source: BoM.*

The tsunami recorded at distant locations from the Tonga volcanic explosion arrived much earlier and was much larger than expected from an earthquake generated tsunami. This event caused great difficulty in the issuance of timely and accurate tsunami warnings for the following three reasons. First, some agencies initially concluded that the earthquake itself, with magnitude 5.8, was not large enough to generate a significant tsunami amplitude around the Pacific Ocean. Second, when the tsunamis did arrive (Figure 2), their early arrival made it very difficult to reliably predict tsunami arrival times for use in warnings. Third, once it became clear that significant tsunami amplitudes had been generated, it was very difficult to reliably predict their heights for use in warnings.



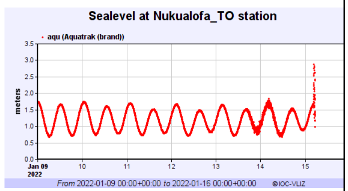


Figure 2*. Left: Recorded tsunami wave heights around the Pacific Ocean. Source: BBC. Right: Tide gauge record at Nuku'alofa from Jan 9 to Jan 16, showing small ripples on the tide between Jan 14-15 before the explosion at the end of the record.*

The purpose of this Briefing Note is to seek explanations of why the Tonga tsunami arrived much earlier and was much larger than expected around the Pacific Ocean for an earthquake generated tsunami. The tsunami recorded in the Tonga islands, which was 0.82 m high at Nuku'alofa but locally reached heights of 15 m, is not addressed here.

Volcanic eruption and earthquake

The Tonga volcanic eruption coincided with a magnitude 5.8 earthquake which appears not to have occurred on a fault, because it does not have a double couple focal mechanism. Instead, it is likely that the earthquake was caused by gravitational collapse within the volcano. Even if the earthquake had resulted from a shear dislocation of a fault, the rupture area and displacement on the fault would not be large enough to displace a volume of water large enough to generate a tsunami of size. It is also possible that submarine landslides contributed to the tsunami.

The United States Geological Survey reported that the earthquake occurred at 2022-01-15 04:14:45 (UTC) at a depth of zero km., corresponding to local time 2022-01-15 17:14:45 in Tonga and 15:14:45 (i.e. 3:15 pm) in Sydney. The origin time of the volcanic explosion is reported to lie in the range of 17:10 (Power, 2022) to 17:20 (GeoNet News) local time. It seems reasonable to assume that the earthquake was related to rapid deformation within the volcano that led to the explosion, and that the earthquake and explosion had the same origin time of approximately 3:15 pm, Sydney time.

Early arrival of the tsunami around the Pacific rim

The tsunami arrived earlier than predicted throughout the Pacific basin. For example, it arrived about 2.5 hours early in Japan (expected travel time of about 10.5 hours from Figure 1; actual travel time of about 8 hours). In Sydney, the predicted travel time of 6 hours from Figure 1 would give an expected arrival time of about 9:15 pm, but the first tsunami arrived just after 6 pm (Power, 2022), over 3 hours earlier, corresponding to a travel time of 2.75 hours. Meanwhile, the air pressure wave resulting from the volcanic explosion was recorded in Sydney shortly after 6pm (right side of Figure 1), minutes before the first tsunami arrival. This suggests that, at least in the first several hours at locations around the Pacific rim, the tsunami was not an earthquake generated tsunami. Unless submarine landslides preceded the explosion, the same would apply to them. The eruptions the previous day resulted in collapse of the caldera, leaving most of the volcano submerged, as shown in a satellite image taken about two hours before the explosion (right side of Figure 2 in Risk Frontiers (2022) Briefing Note 458). However, the eruption and collapse generated only minor disturbances in the tide gauge record at Nuku'alofa, as shown on the right side of Figure 2, indicating that it was not the source of an early Pacific-wide tsunami. Instead, we show next that the tsunami was apparently generated by the interaction of acoustic gravity waves (caused by the explosion) with water gravity waves (tsunami).

Origin of the tsunami recorded in the Caribbean Sea

An earthquake generated tsunami cannot directly propagate from the equatorial east Pacific Ocean across Central America into the Caribbean Sea. However, a small tsunami was observed in Mayaguez, Puerto Rico following the Tonga explosion (Figure 3). Barometric pressure readings in Figure 3 indicate that the acoustic wave arrived in Mayaguez just before the tsunami, suggesting that the acoustic wave acted as a local source generating a tsunami within the Caribbean Sea

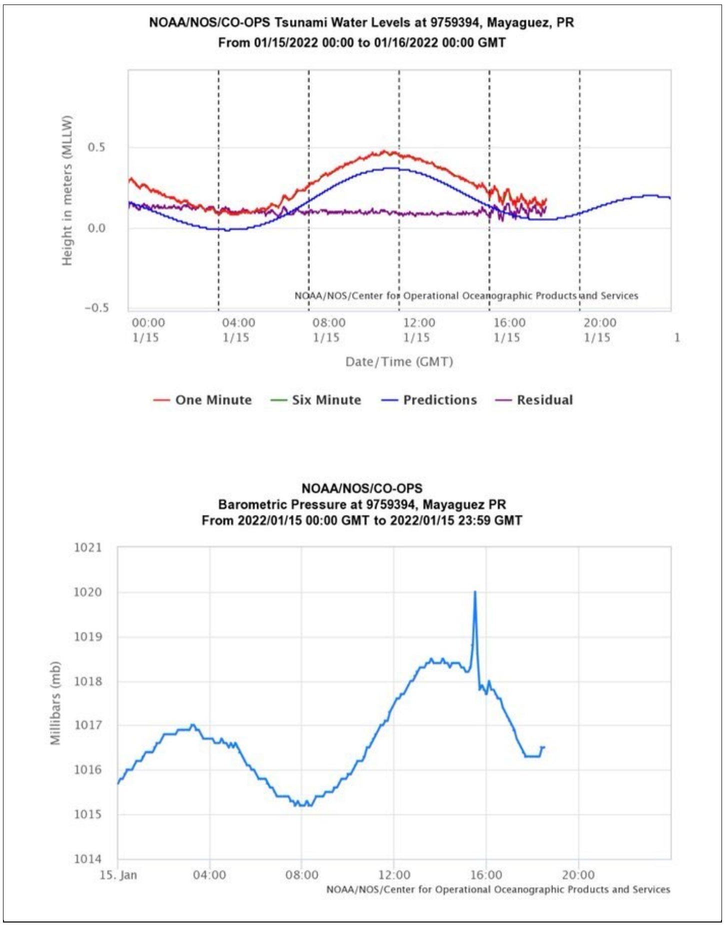


Figure 3: *Tide gauge (top) and barograph (bottom) of the Tonga explosion at Mayaguez, Puero Rico. The purple line in the top panel shows the record after removal of the tides. Source: Dr Greg Dusek, NOAA.*

Similar observations of acoustic waves and tsunamis from the Krakatau explosion

The barograph of the Tonga explosion recorded in Reading, UK in Figure 4 shows a long period acoustic wave (over one hour in period) which travelled at about 1225 km/hour, which is faster than the speed of tsunamis in deep water (about 800 km/hour). The 1883 Krakatau eruption appears to be the only comparable example of a distant tsunami generated by a volcanic explosion (Press and Harkrider, 1966; Carayannis, 2003; Gabrielson, 2010). The barographs of the Krakatau explosion recorded in Aberdeen and Bombay shown in Figure 4 are similar to that of the Tonga explosion, with very long periods, over an hour for one full cycle of motion.

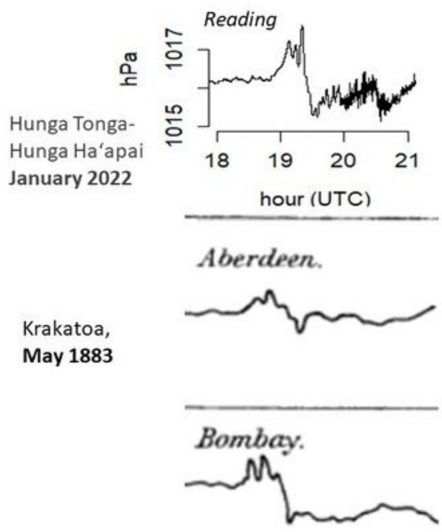


Figure 4*. Barograph from the Tonga explosion at Reading U.K (top); and Aberdeen and Bombay recordings of the 1883 Krakatau explosion (centre and bottom). Source: BBC.*

Observation of acoustic gravity waves from the Tonga explosion

Images collected by the Atmospheric Infrared Sounder (AIRS), mounted on NASA's Aqua satellite, in the hours after the eruption of the Hunga Tonga–Hunga Haʻapai volcano show that the event generated atmospheric gravity waves, which appear as concentric circles in Figure 5, involving vertical oscillations of air molecules in an air column extending from the surface to the ionosphere (elevation of 50 km; Adam, 2022), transferring energy and momentum vertically through the atmosphere. The waves shown in Figure 5 appear to show normal dispersion, with the earliest (and most distant) waves having higher phase velocity and longer wavelengths and periods, and the latest (and closest) waves having lower phase velocity and shorter wavelengths and periods, as discussed below in reference to the left side of Figure 6.

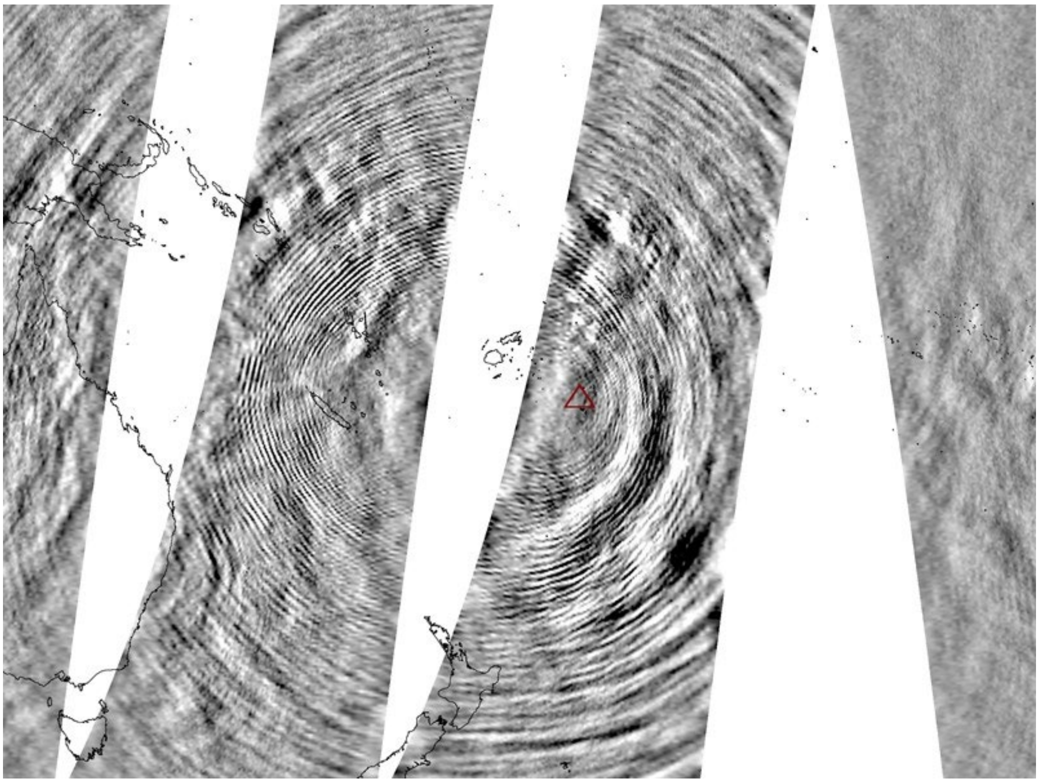


***Figure 5**. Images from the Atmospheric Infrared Sounder on NASA's Aqua satellite showing concentric acoustic gravity waves. Credit: Lars Hoffmann, Jülich Supercomputing Centre. AIRS Level-1 data by NASA DES DISC.*

Coupling of acoustic gravity waves with water gravity waves (tsunami)

Press and Harkrider (1966) showed that acoustic gravity waves can excite water gravity waves (tsunami) having the same phase velocity. The left side of Figure 6 shows the dynamic ratio of sea surface displacement to pressure as a function of phase velocity for fundamental acoustic gravity waves (GR_o) and water gravity waves (GW_o) as well as higher mode GR waves. The vertical scale, which is logarithmic, shows that the amplification is at least ten times greater than the hydrostatic value (with only the acoustic gravity wave) in the phase velocity range of 195 to 230 m/s, corresponding to 702 to 828 km/hour. This range of phase velocities corresponds to a range of higher modes with periods successively increasing with increasing phase velocities.

The right side of Figure 6 shows the tide gauge record at Colon, Panama from the Krakatau explosion. Arrows show theoretical arrival times of GR_o and GW_o for the short (I) and long (II) great circle paths, and the theoretical tsunami arrival time without acoustic coupling. The sea waves begin and then reach large amplitudes (due to resonance) in the interval between the GR_o and GW_o arrival times, as expected from theory, well ahead of the theoretical tsunami arrival time. Colon is almost at the antipode of Krakatau, so the short (arriving from the west) and long (arriving from the east) great circle path arrivals occur close to each other. Colon is on the east coast of Panama, so the tsunamis arrive on the long path from the east from Krakatau. Press and Harkrider (1966), Latter (1981), Carayannis (2003) and Gabrielson (2010) pointed out the arrival times of the Krakatau tsunami recorded in Honolulu, San Francisco and Cardiff, Wales are also much too early for them to have propagated entirely through the oceans.

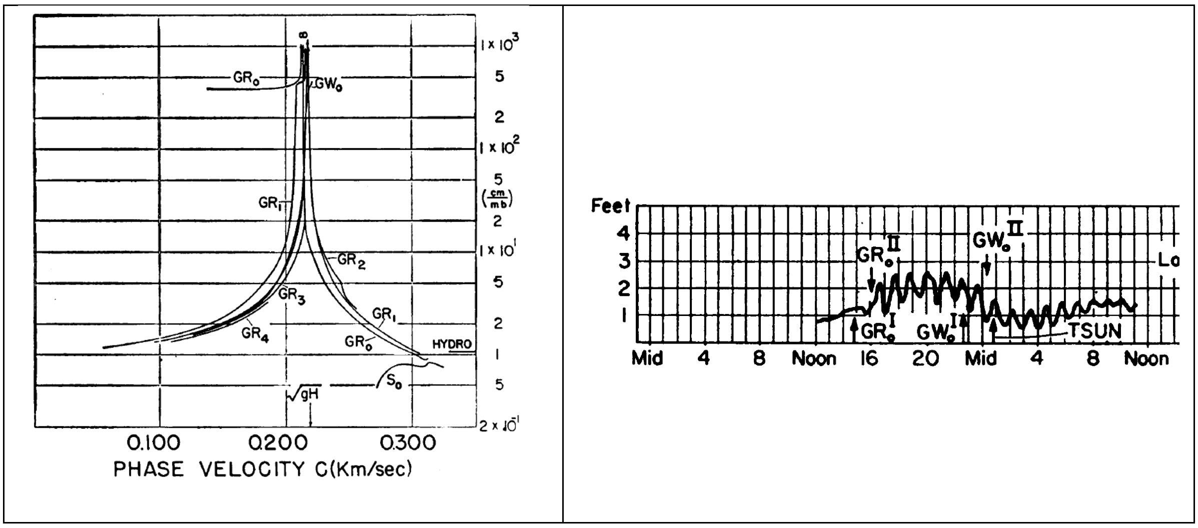


Figure 6. *Dynamic ratio of sea surface displacement to pressure as a function of phase velocity for fundamental acoustic gravity waves (GR_o) and water gravity waves (GW_o) as well as higher mode GR waves, demonstrating resonance. Right: Tide gauge records at Colon, Panama. Arrows show theoretical arrival times of GR_o and GW_o for the short (I) and long (II) great circle paths, and the theoretical tsunami arrival time without acoustic coupling (TSUN). Source: Press and Harkrider, 1966.*

Schematic diagram of tsunami generation by a volcanic explosion

The origin of the tsunami generated by the Tonga explosion is illustrated schematically by Watada (2022) in Figure 7. The explosive eruption causes a strong acoustic gravity wave to spread out, generating a tsunami by interacting with the ocean as it reaches the vicinity of Japan. The tsunami arrived well before the expected arrival time for an earthquake generated tsunami because acoustic gravity waves have faster phase velocities than water gravity waves (left side of Figure 7). Following the earlier arrival of the first acoustic wave mode, higher mode acoustic gravity waves, with shorter wavelengths and slower phase velocities matching those of water gravity waves (tsunamis), cause resonance that amplifies the height of the tsunami. This explains why the tsunami was much higher than that predicted for an earthquake generated tsunami.

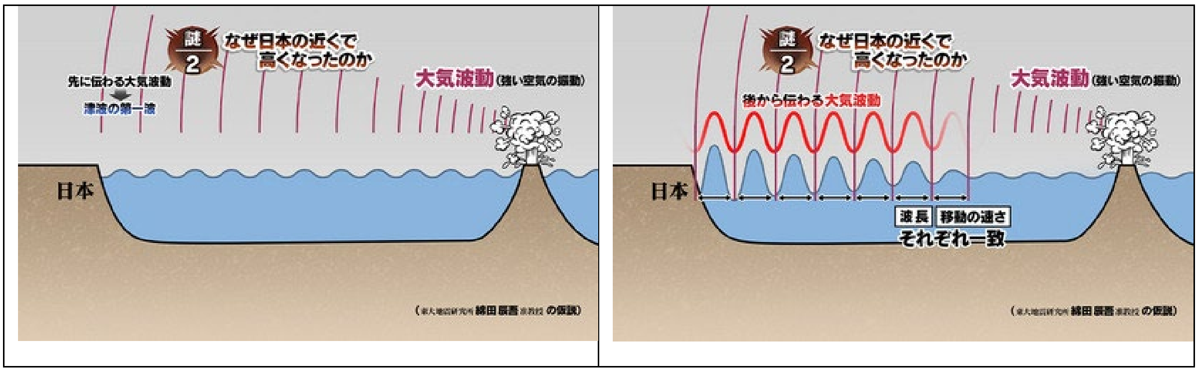


Figure 7. *Left: Generation of the initial tsunami by the acoustic gravity wave close to the recording site. Right: Generation of later arriving tsunami by the coupling of the acoustic gravity waves with ocean gravity waves having similar phase velocities, causing resonance. Source: Watada (2022).*

Conclusions

We have shown evidence, confirmed by theory and the example provided by the 1883 Krakatau explosion, that the tsunami generated by the Tonga explosion were generated by the interaction of acoustic gravity waves (caused by the explosion) with water gravity waves (tsunami). This explains why the tsunami arrived much earlier and much larger than expected from an earthquake generated tsunami.

This event caused great difficulty in the issuance of timely and accurate tsunami warnings for the following three reasons. First, some agencies initially concluded that the earthquake itself, with magnitude 5.8, was not large enough to generate a significant tsunami amplitude around the Pacific Ocean. Second, when the tsunamis did arrive, their early arrival made it very difficult to reliably predict tsunami arrival times for use in warnings. Third, once it became clear that significant tsunami amplitudes had been generated, it was very difficult to reliably predict their heights for use in warnings.

Dart buoy data from the Tonga explosion (GNS Science, 2022; Titov et al., 2022) recorded within the deep oceans will be the key to fully understanding the wave generation and propagation mechanisms of these tsunamis. This knowledge will be needed for the accurate forecasting of amplitudes and arrival times of tsunamis generated by volcanic explosions, and the issuance of reliable warnings in future volcanic explosion events.

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