News & views

Earth science

Atmospheric waves boosted tsunami after Tongan blast

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The global tsunami and atmospheric waves that followed the eruption of the Tongan volcano Hunga Tonga–Hunga Ha'apai were observed around the world. Analysing the data could reshape our understanding of such events. **See p.728, p.734 & p.741**

On 15 January 2022, the Tongan volcano known as Hunga Tonga–Hunga Ha'apai (hereafter, Hunga Tonga) erupted explosively, sending a plume of ash as high as 55 kilometres into the atmosphere and causing sonic booms that were heard as far away as Alaska. The eruption triggered the first global volcanic tsunami since the Indonesian volcano Krakatau created deadly waves in 1883 – making Hunga Tonga the first eruption of its kind in the modern satellite era. Wright *et al.*[1] (page 741), Lynett *et al.*[2] (page 728) and Omira *et al.*[3] (page 734) have now seized this opportunity to study the remarkable wave phenomena that the eruption caused, using a range of space- and Earth-based observational techniques.

Volcanic tsunamis can be generated by several mechanisms[4]. In some cases, the eruption causes a landslide known as flank collapse (Fig. 1a), or creates highly mobile mixtures of gases and volcanic ash known as pyroclastic flow (Fig. 1b), both of which can trigger a tsunami. In the case of submarine volcanoes, the underwater explosion can cause a tsunami (Fig. 1c), or a tsunami can be generated when the ejected volcanic material comes crashing back into the sea, in an event known as eruptive column collapse (Fig. 1d). The hollow that forms after a magma chamber has been emptied, known as a caldera, can also trigger a tsunami when it collapses (Fig. 1e). Often, several mechanisms occur within one eruptive sequence, as seems to have been the case for Hunga Tonga. However, the evidence from the three latest studies suggests that atmospheric disturbances caused by the eruption were responsible for amplifying the result, creating a wave known as a meteotsunami (Fig. 1f).

Wright *et al.* used satellite and land-based imaging to track two types of atmospheric wave, Lamb waves and gravity waves, which were both observed after the eruption. Lamb waves are acoustic-gravity waves that compress the atmosphere, but also displace it vertically. These waves span the entire atmosphere and travel close to the speed of sound – they were observed circling the globe several times in the days after the blast. Gravity waves travel more slowly, zigzagging up and down through the stratosphere. As they radiate out, they disperse into a train of waves in which those with longer wavelengths travel faster than shorter-wavelength waves. The satellite images of the Hunga Tonga eruption revealed fascinating features, including a Lamb wave slowing over South America and partially reflecting off the Andes. Understanding and modelling these details could provide crucial insights to refine our current atmospheric models.

Generally, volcanic tsunamis cause destruction within about 100 kilometres of the volcano. The Hunga Tonga eruption caused an atmospheric-pressure anomaly (the Lamb wave) that reinforced the water waves, enabling them to travel thousands of kilometres. Lynett *et al.* gathered evidence of tsunami impacts both in Tonga and throughout the Pacific Ocean, and developed a simple model for how the tsunami might have been generated. The model includes a blast characteristic of the initial explosion; an instantaneous depression of 100 metres in the water surrounding the volcano, representing a caldera collapse; and an approximation of the air-pressure wave that followed.

Given the limited information about the

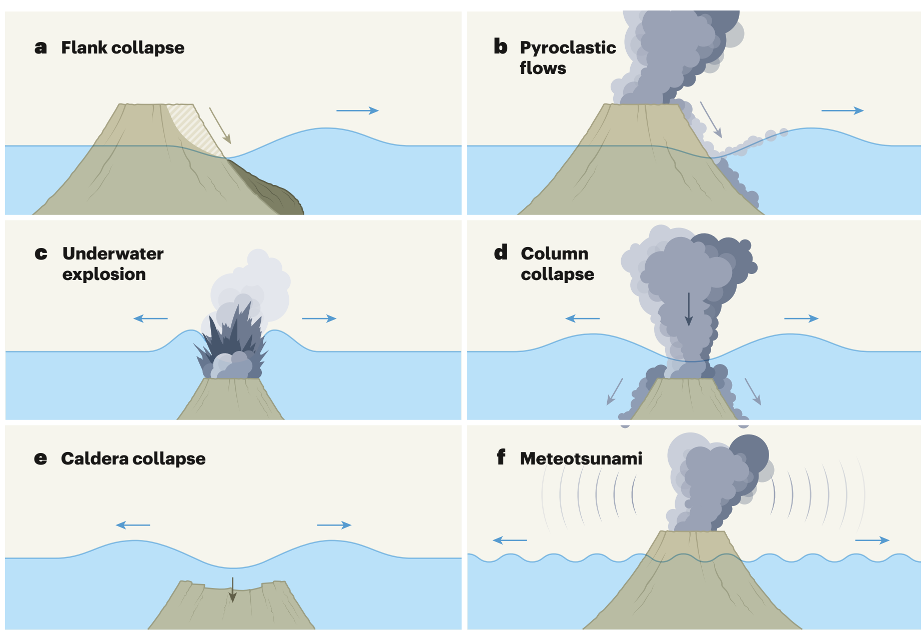

Figure 1 | Mechanisms through which volcanic tsunamis can be generated. Wright *et al.*[1], Lynett *et al.*[2] and Omira *et al.*[3] studied the wave phenomena created by the eruption of the Hunga Tonga–Hunga Ha'apai volcano in Tonga. Several factors can lead to a volcano generating a tsunami[4]. **a**, Volcanic eruptions can trigger a tsunami by causing landslides, known as flank collapse. **b**, Blasts can generate volcanic-ash (pyroclastic) flow, which can cause a tsunami. **c**, Tsunamis can be induced by underwater explosions from submarine volcanic eruptions. **d**, The collapse of the eruptive column back into the sea can also cause a tsunami. **e**, The hollow that forms after a magma chamber is emptied, known as a caldera, can induce a tsunami when it collapses. **f**, Atmospheric disturbances caused by an eruption can create or amplify water waves, creating a wave known as a meteotsunami.

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Figure 2 | Satellite image of Tongan volcano Hunga Tonga–Hunga Ha'apai. The missing central crater in this satellite image, taken 2 hours before the main eruption on 15 January 2022, is evidence of flank collapse from the previous day's eruption, which caused a moderate tsunami.

eruption available during this initial phase, Lynett and colleagues' basic approach is appropriate, and the results show good agreement with data obtained from tide gauges and deep-sea buoys that are set up to monitor tsunamis. Calderas often collapse in several steps and over a time frame that is too slow to generate substantial waves, so ascribing the water depression to a caldera collapse might not be accurate. However, this sort of depression has been shown to be effective for modelling tsunamis generated by explosions[5], and possibly also pyroclastic column collapse. As understanding of volcanic eruptions improves, more-detailed tsunami models will no doubt be developed. And reverse engineering using tsunami modelling could, in turn, reveal features of the eruption.

One aspect that Lynett *et al.* overlooked was the moderate tsunami that was generated on the previous day, 14 January. This event was probably the result of flank collapse of the central cone joining the two islands of Hunga Tonga and Hunga Ha'apai, which can clearly be seen in a satellite image taken on 15 January before the main eruption (Fig. 2). It is possible that this initial tsunami contributed to the fact that remarkably few deaths were recorded in Tonga, by making people aware of the dangers of volcanic tsunamis.

Omira *et al.* take up the story where Lynett and colleagues' study ends, explaining how the tsunami became a truly global phenomenon that was measured as far away as the Caribbean and Mediterranean seas — and even caused two deaths in Peru. The authors documented the times at which the tsunami arrived at different places around the world, and showed that these times correlated with the velocity of the atmospheric acoustic-gravity waves, rather than the shallow water-wave speed, which is the upper limit for waves travelling freely in the ocean, and is usually used for tsunami travel-time predictions[6].

On this basis, Omira *et al.* developed a model suggesting that the tsunami was generated by a moving air-pressure disturbance, and they demonstrated that this model reproduces tsunami waves far from the eruption site. This meteorological mechanism therefore explains why the Hunga Tonga tsunami had such a global impact, lasting much longer than expected, because it was affected by multiple passes of atmospheric waves as they looped around the globe. Omira and colleagues also showed analytically how the atmospheric waves reinforce the water waves, even when the air disturbance travels considerably faster than that of the water.

These papers offer tantalizing first hints about the mechanism behind the eruption and tsunami, but there is much more to learn. Surveys reported this year have revealed fascinating further details, including the considerable depth of the caldera post-eruption and the fact that the sea floor surrounding the eruption site is covered in pyroclastic deposits (see *Nature* https://doi.org/h3wk; 2022). Hunga Tonga has already caused scientists to rethink our understanding of volcanoes and tsunamis. The science emerging from these observations and those to come could well revolutionize this understanding.

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The author declares competing interests. See go.nature.com/3nlhatd for details.
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