

TSUNAMIS

The wave blown around the world

The atmospheric wave from the Tonga eruption drove faster-than-normal tsunamis

By **Emily E. Brodsky** and **Thorne Lay**

On 15 January 2022, unusual waves appeared in Earth's atmosphere and oceans (1–3). The origin of the waves was clearly the catastrophic volcanic eruption in Tonga, which pummeled the atmosphere with the largest eruptive plume since the 1883 eruption of Krakatoa, Indonesia. On page 95 of this issue, Matoza *et al.* (4) show that the 2022 Tonga eruption generated waves in the water, air, and even in the ionosphere that wrapped around Earth multiple times. Tsunamis appeared to hop across the land into all of the major ocean basins. And on page 91 of this issue, Kubota *et al.* (5) explain that the tsunamis arrived much earlier than expected on the basis of conventional tsunami modeling, and the wave trains lasted much longer than for even the largest earthquakes (5).

Tsunamis are ocean waves with several-hundred-kilometer-long wavelengths that are usually caused by sudden perturbations of the ocean. Giant earthquakes, such as the 2004 magnitude 9.2 Sumatra earthquake, can produce abrupt sea-floor movements that extend as much as 1500 km along the fault rupture on a tectonic plate boundary, displacing the overlying ocean and generating a devastating tsunami. But earthquakes are not the only events that trigger tsunamis—landslides and volcanic eruptions can also displace large volumes of water in the ocean and produce tsunami waves.

Once the water is displaced, tsunamis travel as ordinary gravity waves with buoyancy providing the restoring force. Gravity waves in the ocean include the familiar waves on the sea surface that break on the seashore. Tsunamis are usually governed by the same physics. However, because of their long wavelengths, the speed and path of the gravity waves are determined by the variable depth of the ocean. Investments in tsunami modeling, motivated by the events of the 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami in Japan, have helped

develop forecasting and warning systems for tsunamis that now produce reasonably accurate predictions after earthquakes of when and where tsunamis will occur as well as how high the waves will be.

Surprisingly, the first tsunami arrivals produced by the Tonga eruption were observed several hours earlier than anticipated. Kubota *et al.* explain that the fast and complex tsunamis result from how the ocean interacts with the atmosphere after a volcanic eruption (see the figure). They show that the atmospheric and oceanic dynamics are intimately connected. The atmospheric waves were accompanied by a coupled oceanic wave that traveled at a speed that exceeded that of conventional tsunami gravity waves in the ocean (~200 m/s). The coupled wave can be modeled as an acoustic-gravity wave, which travels by

simultaneously compressing (like a sound wave) while having an accompanying buoyancy force at the air-sea interface. In effect, the air wave blew the tsunami wave across the ocean, even passing over continents and driving new tsunamis when the ocean was again encountered.

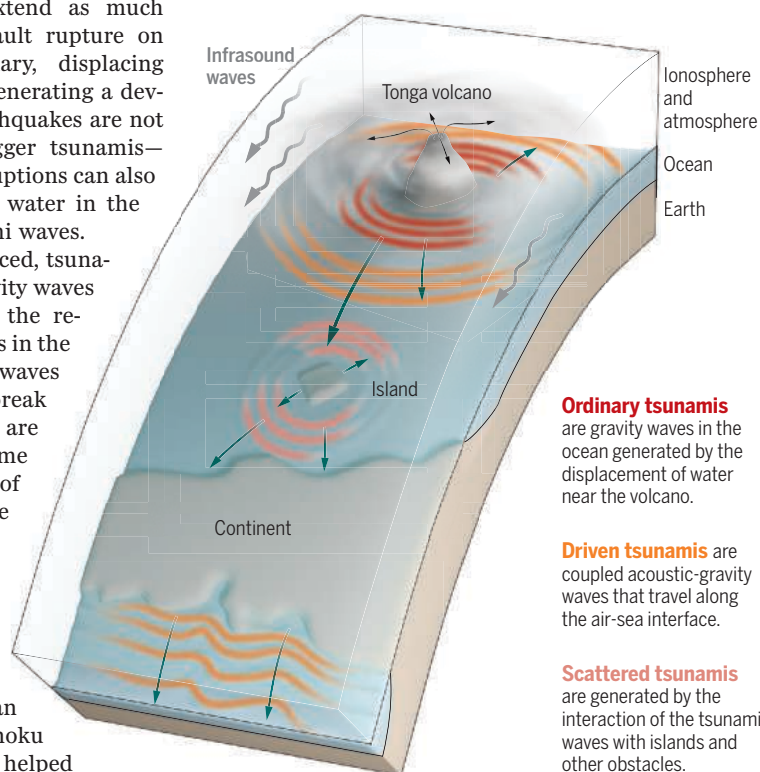
This rare method of tsunami generation has a precedent in the last eruption that produced such strong atmospheric waves. Like the 2022 eruption in Tonga, the 1883 Krakatoa event also produced an intense atmospheric acoustic-gravity wave and infrasound that could be heard up to 3000 miles away (4). In 1955, Press and Ewing (6) noted that air-pressure increases were coincident with initial oceanic waves observed around the world. In 1967, Harkrider and Press (7) went on to analyze the coupled motion of the ocean

and atmosphere to quantify the mechanistic connection. Of course, the data from 1883 were difficult to analyze and the Krakatoa observation stood as an oddity in the annals of tsunami generation until the 2022 eruption in Tonga produced extensive global observations (4).

The wavefield that resulted was captured with unprecedented resolution as explained by Matoza *et al.* The rich data make it clear that very large-scale atmospheric transients of eruptions or atmospheric impacts should be expected to produce large, fast, and complex tsunamis around the world. The volcanic blast produced a nondispersive wave in the atmosphere that traveled along Earth's surface with a pressure oscillation lasting over 2000 s that expanded away from the source at about 315 m/s (4, 5, 8–11). Slower acoustic waves were of high enough frequencies (>20 Hz infrasound) that they could be heard by people in Alaska, more than 6000

Multiple tsunami generation mechanisms

The January 2022 Tonga eruption generated waves in the oceans, atmosphere, and ionosphere as reported by Matoza *et al.*, including unusual tsunamis blown by atmosphere at the air-sea interface as shown by Kubota *et al.*



Ordinary tsunamis

are gravity waves in the ocean generated by the displacement of water near the volcano.

Driven tsunamis

are coupled acoustic-gravity waves that travel along the air-sea interface.

Scattered tsunamis

are generated by the interaction of the tsunami waves with islands and other obstacles.

Department of Earth and Planetary Sciences, University of California Santa Cruz, CA, USA Email: brodsky@ucsc.edu

miles away from the erupting volcano.

In addition, conventional tsunami waves were generated near the source in response to the initial ocean displacement, and scattered tsunami waves were generated as the driven wave encountered variations in ocean depth across the Pacific. This combination of generation mechanisms produced the very long-lasting sequence of tsunami waves, including the largest waves, which were twice as large as the initial atmospherically coupled one (11). Even more elastic waves were produced in the solid earth and were observed on seismometers globally (12).

The 2022 Tonga eruption reawakens curiosity about processes crossing traditional boundaries between Earth systems. Atmosphere–Ocean–Solid Earth coupling is a major focus of climate research, yet observations that directly sample their interaction may have been underutilized. Volcanic eruption studies show that the tools of infrasound and seismology that have traditionally been used to study the solid Earth potentially have much broader uses. New technologies and networks in a data-rich world are providing windows into dynamic interactions between Earth's systems. Oceans, rivers, glaciers, and hurricanes all produce distinctive waves that are now routinely recorded on global networks (13–15). Earth's systems are broadcasting their interactions through multiple types of waves, and now instrumentation is in place to receive their signals. It is up to the scientific community to reach out across the disciplinary boundaries and use the data to ask the right questions about the entire Earth system. ■

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NEURODEGENERATION

Elucidating the causes of neurodegeneration

Investigating phase separation in neurodegeneration highlights evidence needed for causation

By Gregory A. Petsko¹ and Scott A. Small²

How can a given gene, or gene product, or the cellular pathway it serves be determined as causal for neurodegenerative diseases instead of being a consequence of the underlying pathology? There are questions about the current theories that explain neurodegeneration, with therapeutic strategies producing disappointing results. On page 46 of this issue, Zhou *et al.* (1) attempt to address whether the aberrant phase separation of protein domains of low amino acid sequence complexity are causally pathogenic in several neurodegenerative diseases, including a form of frontotemporal dementia. Their approach has potential application in identifying causative factors in a range of disorders, as well as to the formation of membraneless organelles in normal cells.

In 1884, Robert Koch and Friedrich Loeffler proposed postulates to establish that a microorganism caused an infectious disease (2). Despite many iterations of Koch's postulates since (3), the concept of a set of criteria that should be satisfied to determine causality for an infectious disease remains useful. Nowhere is such rigor more needed than in the case of neurodegenerative diseases. The complexity, chronicity, and relative inaccessibility to experimentation of the human brain, and lack of good animal models, as well as the phenotypic heterogeneity and age dependence of most of these disorders make finding causal biological pathways very difficult. Consequently, specific criteria to establish causality for a neurodegenerative disease and to validate a target and therapeutic approach might be useful. Ideally, given the complexity of the problem, such postulates should reflect an integrative biology approach (see the figure).

A set of criteria are proposed, integrating evidence from human molecular biology

(whether key molecules of the pathway are dysregulated in the disease), cellular biology (when disrupted, whether the pathway causes the disease's cardinal cellular pathologies), and anatomical biology (when disrupted, whether the pathway causes the disease's cardinal anatomical pathology). In the case of Alzheimer's disease, the hypothesis that misprocessing of the amyloid- β precursor protein (APP) produces cytotoxic extracellular amyloid plaques fulfills parts of the first two criteria. But amyloid plaque deposition is not primarily observed in the trans-entorhinal cortex (TEC), where neurodegeneration begins in Alzheimer's disease—an anatomical mismatch between plaques and neurodegeneration noted by Alzheimer himself (4). The TEC is important in short-term memory and navigation, which become disrupted in Alzheimer's disease. Two promising new hypotheses for the causes of neurodegeneration in Alzheimer's disease—dysfunction of the innate immune system in the brain (5) and defects in endosomal protein trafficking (6)—are not mutually exclusive; the latter may fulfill all three criteria (7).

Zhou *et al.* describe experiments aimed at satisfying these criteria in an attempt to resolve an ongoing controversy about how low-complexity sequence domains form membraneless organelles (8) but also to identify a causal mechanism for several neurodegenerative diseases. It has been known for more than a century that eukaryotic cells contain phase-separated liquid-like droplets, but interest in their composition and function waned. However, in 2009, germline P granules in *Caenorhabditis elegans* were shown to be liquid droplets that displayed similar behavior to that of oil in water (9). Further work revealed that such phase separation was common, especially for some protein-RNA complexes, and it was proposed that the resulting membraneless organelles likely played important functional roles in the regulation of gene expression and nuclear import (10) by providing a way to temporarily organize critical components without the complexity of transporting molecules across a membrane.

In 2012, amyloid-like fibers were identified in hydrogels formed from low-complex-

¹Ann Romney Center for Neurologic Diseases, Department of Neurology, Brigham & Women's Hospital and Harvard Medical School, Boston, MA, USA. ²Taub Institute for Research on Alzheimer's Disease and the Aging Brain, Department of Neurology, Columbia University, New York, NY, USA. Email: gpetsko@bwh.harvard.edu; SAS68@columbia.edu

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Emily E. BrodskyThorne Lay

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