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KRAKATOA AND THE ROYAL SOCIETY: THE KRAKATOA EXPLOSION OF 1883

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On 27 February 2010, a magnitude 8.8 earthquake struck near the coast of Chile. Media coverage was immediate and intense, focusing not only on local destruction but also on the tsunami launched across the Pacific Ocean. Coastal areas of Hawaii were evacuated and television cameras swept the beaches hoping (but failing) to capture landfall of a monster wave. Less glamorous was the network of National Data Buoy Center (NBDC) ocean buoys that can be accessed in nearly real time through the internet.¹ Buoy 43412, in the Pacific about 400 km southwest of Manzanillo, Mexico, showed the tsunami's passage as a 0.1 meter rise and fall over 20 minutes, superimposed on the normal tidal variation in ocean height. The tsunami passed this buoy almost 10 hours after the earthquake. (At least one television network showed output from an NBDC data buoy; however, the graphic actually showed a data glitch of greater than 10 meters in height rather than the much smaller tsunami signature. Easy access to data is a double-edged sword.) We take global and immediate access to data for granted. Immediate access is recent; however, global observations have been important much further back.

On 27 August 1883, the island of Krakatoa was virtually destroyed by an immense volcanic explosion. The resulting pressure wave was recorded worldwide for days afterward and is one of the most frequently-cited acoustical events of global proportion. Observations of the pressure wave from the explosion were not restricted to one or two locations; more than 50 weather stations around the world recorded the wave's passage. Several stations recorded as many as seven passages as the wave orbited the globe. Photographic and pen-and-ink recordings of barometric pressure were forwarded to London and the initial analyses were reported in a pair of papers, one by R. H. Scott and one by Lt. Gen. R. Strachey, in December, 1883.

In January of 1884, the Royal Society of London commissioned a

“The barograph in Glasgow recorded seven passages: at 11 hours, 25 hours, 48 hours, 59 hours, 84 hours, 94 hours, and 121 hours (5 days) after the eruption.”

collection of geophysical observations related to the Krakatoa eruption. Shortly thereafter, the investigations of the Royal Meteorological Society were merged with those of the Royal Society and the Krakatoa Committee of the Royal Society (Symons, 1888) was formed.

Clearly, the explosion's pressure wave was a remarkable, global phenomenon. About 4 hours after the explosion, the pressure pulse appeared on a barograph in Calcutta. In 6 hours, the pulse reached

Tokyo; in 10 hours, Vienna; and in 15 hours, New York. After converging through the antipodal point near Medellin, Columbia, the wave was seen again in New York 23 hours after the explosion; in Vienna again at 26 hours; in Tokyo again at 31 hours; and in Calcutta again at 32 hours. The barograph in Glasgow recorded seven passages: at 11 hours, 25 hours, 48 hours, 59 hours, 84 hours, 94 hours, and 121 hours (5 days) after the explosion.

While the distribution of observing stations shown in Fig. 1 was far from uniform—almost half of the stations were in Europe and about one quarter were in the British Isles—several distinct paths were sampled. The stations in Toronto, New York, Washington (DC), and South Georgia Island sampled a path that passed nearly over the poles. The stations in Mauritius and Luanda (in present-day Angola) sampled a nearly equatorial path. Many of the rest of the stations sampled orbits inclined roughly midway between the equator and the polar path.

From the global distribution of observing stations, the authors of the Krakatoa Report constructed equal-time contours and these

contours paint a fascinating picture² of the evolution of the wave front (Figs. 2 and 3). If the speed of propagation had been constant and the Earth spherical, the wave would have started from Krakatoa and expanded uniformly until halfway around the globe. As the wave front continued past the halfway point, it would have begun



Fig. 1. The Krakatoa pressure wave was recorded at more than 50 stations around the world. The stations that supplied records to the Royal Society are shown here as red dots. The map projection above is a hemispherical view with Krakatoa at the center of the right projection and the antipodal point at the center of the left projection. Re-drafted from Symons, 1888.

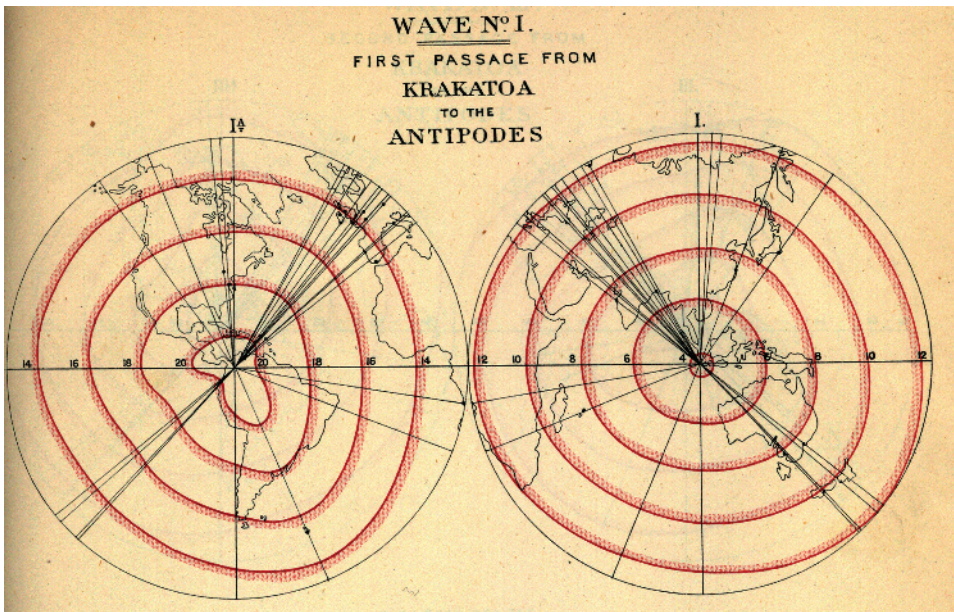


Fig. 2. One of a number of figures included in the Royal Society report on Krakatoa (Symons, 1888) illustrating the progression of the pressure wave from the explosion site. The contours are reconstructed for every two hours starting at 04:00UTC (about one hour after the main explosion) on 27 August, 1883, with the earliest contour, labeled “4”, on the right. This is labeled the “first passage from Krakatoa to the antipodes.” The last contour shown in this plate is the contour near to and approaching the antipodal point at 20:00UTC on the left diagram, labeled “20”. An animation covering the five-day period of detectable signals is discussed in the sidebar of this article.

to contract. As it moved toward the antipodal point, it would have collapsed to a point and re-emerged as if from a secondary source at the antipodes. The cycle of propagation from Krakatoa to the antipodes and back would have continued until the amplitude decayed into the background of normal barometric fluctuations.

This is only roughly what happened. In reality, the circular wave front distorted as it traveled because the speed of propagation varied along the route (See sidebar). Consider the contours at 36 and 38 hours from 00:00 GMT (33 and 35 hours from the main explosion) on 17 August (Fig. 3). After almost a complete circuit around the Earth, these contours show the development of three distinct lobes. G. I. Taylor (1929) succeeded in fitting the three-lobed contour by assuming a wind with direction parallel to latitude lines and a speed that varied with latitude. This assumed profile simulated the expected easterly winds in the tropics and westerly winds at middle latitude. The fit, $A\cos 3\theta - B\cos\theta$ where θ is latitude, $A = 7.6$ m/s, and $B = 3.7$ m/s, produced a maximum wind speed of 3.9 m/s from the east (at the equator) and a maximum wind speed of 9.5 m/s from the west (at 57 degrees latitude).

Roughly, the wave took a day and a half to make each complete circuit of the globe. The apparent speed of propagation³ ranged from 300 m/s to 325 m/s depending on the direction and inclination of the path. The observed

speed range also triggered an argument. Some argued that the wave was an ordinary acoustic wave based on its speed; others rejected that notion because the frequency of the wave was so low and the wavelength so long. A popular view was that the wave in the atmosphere was similar to a long-period surface wave on the ocean. In fact, the wave was neither a long-period surface wave nor a pure compressional acoustic wave. The sound speed, the wind, and buoyancy all influenced the propagation; a reasonable theory would mature in the decade following the explosion.

Lord Rayleigh (1890) examined the nature of waves in an isothermal atmosphere having a density that decreased exponentially with altitude. Although Rayleigh does not mention Krakatoa in this paper, it is hard to believe that he was not influenced by the contemporary arguments about the observed propagation speed of the

Krakatoa wave. (However, Rayleigh did mention a perplexing issue related to wave propagation and natural frequencies in the atmosphere—the normal semi-diurnal component in barometric pressure is far too large to attribute to tides in the atmosphere. He proposed that a tidally driven resonance in the atmosphere might be responsible.) Lamb (1911) extended the theory to include vertical variations in temperature.

The solutions of Rayleigh and Lamb accounted for both compressibility and buoyancy. They each explained that several wave types were possible and they connected the analytical solu-

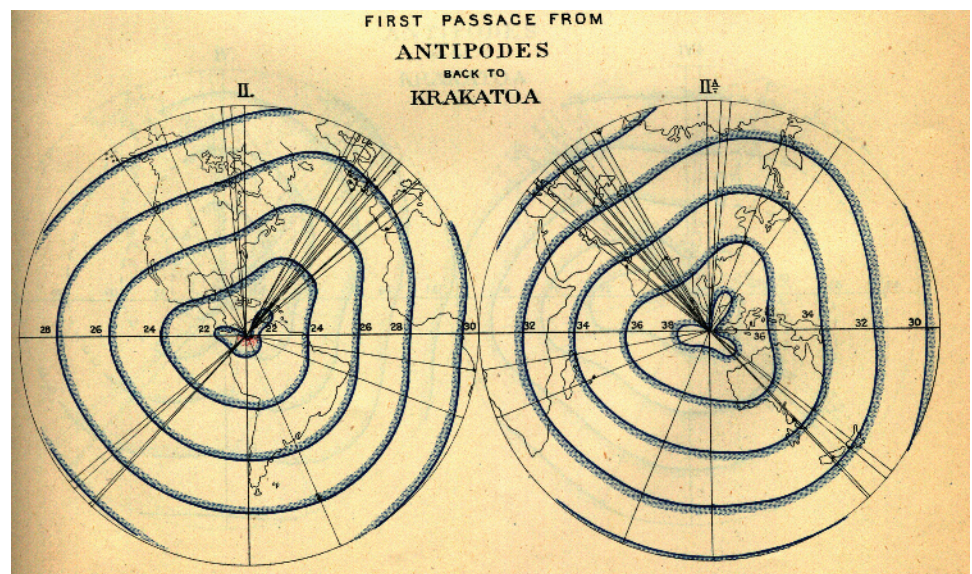


Fig. 3. The second in a series of seven figures showing the progression of the pressure wave. This figure shows the progression after passing through the antipodal point and continuing back toward Krakatoa. The contour colors indicate the direction: red (Figure 2) toward the antipodal point; blue (above) back toward the explosion site. The last contour (labeled 38 for 38 hours after 00:00UTC on 27 August 1883) shows clearly the three-lobed pattern produced by unequal travel times along different paths.

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Shortly after the print copy of this issue is mailed, it will also be published in the Acoustical Society of America's Digital Library. The Table of Contents may be reached directly by going to your internet browser and typing the following Uniform Resource Locator (URL) in the address block: <http://scitation.aip.org/dbt/dbt.jsp?KEY=ATCODK&Volume=6&Issue=2>. At some point in the download process you will probably be asked for your ID and Password if you are using a computer that is not networked to an institution with a subscription to the ASA Digital Library. These are the same username and password that you use as an ASA member to access the *Journal of the Acoustical Society of America*. Open the abstract for this article by clicking on Abstract. At the bottom of the abstract will be a link. Click on the link and a zipped folder (GabrielsonData.zip) will be downloaded to your computer (wherever you usually receive downlinks). Unzip the file. Open it and the video clip should play. (If it doesn't start, click on the arrow icon. This clip does not have sound.) The video clip was recorded in QuickTime's .MOV format. If you have difficulty in playing it, you might download the PC or MAC version of *VLC Media Player* from www.videolan.org. This is a non-profit organization that has created a very powerful, cross-platform, free and open source player that works with almost all video and audio formats. Questions? Email the Scitation Help Desk at help@scitation.org or call 1-800-874-6383.

tions to the view that the wave may be similar in nature to a long wave on the surface of the ocean. Much earlier, G. B. Airy (1845) showed that a surface wave on the ocean, if its wavelength is much larger than the ocean depth, would travel at a speed equal to the square root of the product of the ocean depth, h , and the acceleration of gravity, g . If the ocean-wave analogy is valid, the key to finding the speed of propagation in the atmosphere would be to find the effective height, h , of the atmosphere. The best guess was that the effective height is the height of a constant-density layer that produces the same surface pressure as the actual atmosphere.

John LeConte (1884) provides an interesting historical sidelight in his discussion of the propagation-speed argument. He paraphrases one of Newton's expressions for the speed of sound in air: "the velocity of sound...[is] equal to that which a heavy body would acquire in falling vertically through half the height of the homogeneous atmosphere whose...pressure

measures its elasticity." (Newton's expression is itself a counter-argument to those who claim that an explanation in words is always better than an equation!) LeConte notes that this reasoning, if applied to the ocean, gives Airy's result for the propagation speed of long-wavelength water waves.

However, in the case of water waves, Airy's formula gives surface-wave propagation speeds far slower than the speed of propagation for compressional waves. For example, the tsunami produced by the 2010 Chilean earthquake traveled the 6800 km from the epicenter to NDBC Buoy 43412 in 9 hours and 45 minutes for a speed of 193 meters per second. This implies an average water depth of 3800 meters, which is entirely reasonable given the path, but is far slower than the nearly 1500 meter per second speed of compressional acoustic waves in the ocean.

In contrast, Newton's expression gives a speed only about 20 percent lower than the speed of ordinary acoustic waves in the atmosphere. (A constant-density atmosphere is, of course, ridiculous but if the surface pressure from a more realistic model with exponentially decreasing density is used to find the equivalent constant-density layer thickness, this thickness—the "scale height"—also produces the isothermal speed of sound.) The salient point here is that, *for an ideal gas*, the speed of sound calculated from the gas compressibility is close to the wave speed calculated from the long-surface-wave approximation. Therefore, given the rudimentary state of knowledge concerning the vertical distribution of temperature in the atmosphere, the fact that the Krakatoa pressure pulse traveled at a speed nearly equal to the ordinary speed of sound was evidence neither for nor against the pure acoustic nature of the wave.

Propagation calculations, even simplistic calculations based

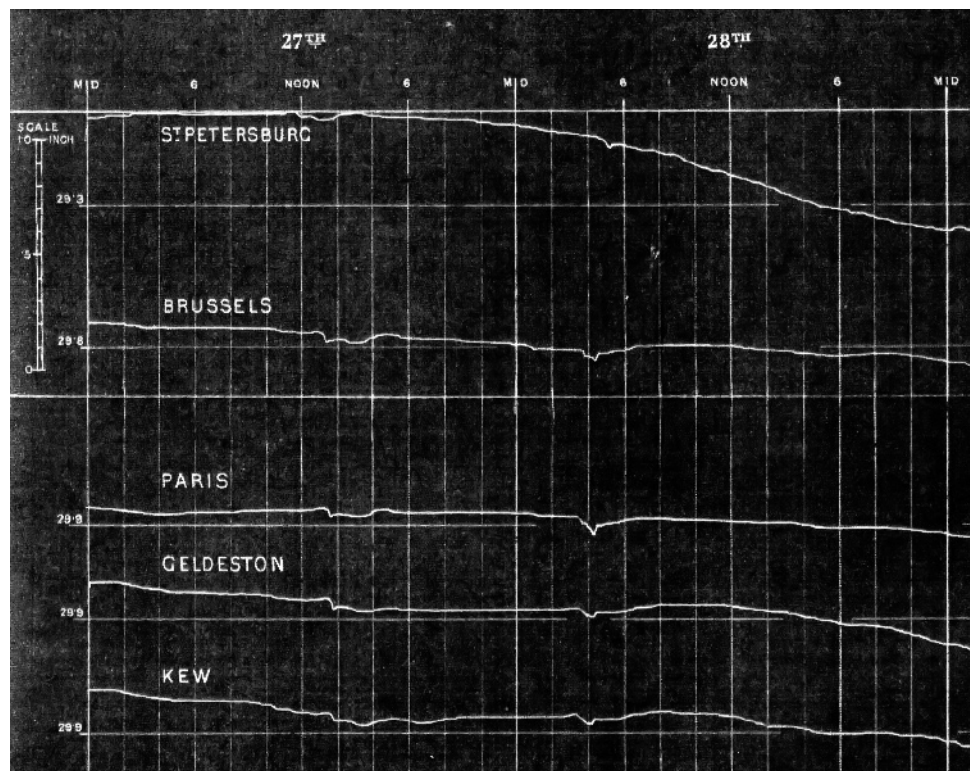


Fig. 4. Barograph traces from several stations for the first two passages of the wave (reproduced from Scott, 1883). All of these stations are in Europe. They show the first passage between 12:00 and 14:00 UTC on the 27th and the second passage between 04:00 and 06:00 on the 28th. The horizontal divisions are two hours apart. The vertical scale shown at the upper left represents one inch of mercury (about 3300 Pa).

on effective height, require knowledge or assumption regarding the vertical temperature profile in the atmosphere since both sound speed and density depend on temperature. Taylor (1929) made the assumption common to the early part of the 20th century: that the temperature in the atmosphere decreased at about 5°C per kilometer (about half the “adiabatic lapse rate”) to an altitude of about 13 km (the “tropopause”) and was constant above that point. Taylor’s calculation produced a value for wave propagation that was within a few percent of the observed speed. He also argued that these calculations supported Rayleigh’s natural-frequency interpretation of the semi-diurnal barometric pressure fluctuations.

A decade after Taylor’s paper, C. L. Pekeris (1939) published his analysis of modal propagation in the atmosphere. Pekeris improved the assumption regarding the vertical temperature variation in the atmosphere by including a zone of stratospheric heating—the result of absorption in the region of solar ultraviolet interaction with oxygen and ozone. He found that there would be two distinct modes of propagation, each with its own characteristic propagation speed. In the first mode, the oscillatory particle motion would be in phase at all altitudes and, in the second mode, there would be a reversal in the phase of particle motion at some intermediate altitude. He found several barograph records from the Krakatoa explosion that seemed to show the second mode, albeit weak, but he concluded that the major events were the result of the first mode. Furthermore, the predicted speed for the first mode was close to the speed observed.

As for the pulse itself, the recorded peak pressures at distant stations on the first circuit ranged from a few tens of pas-

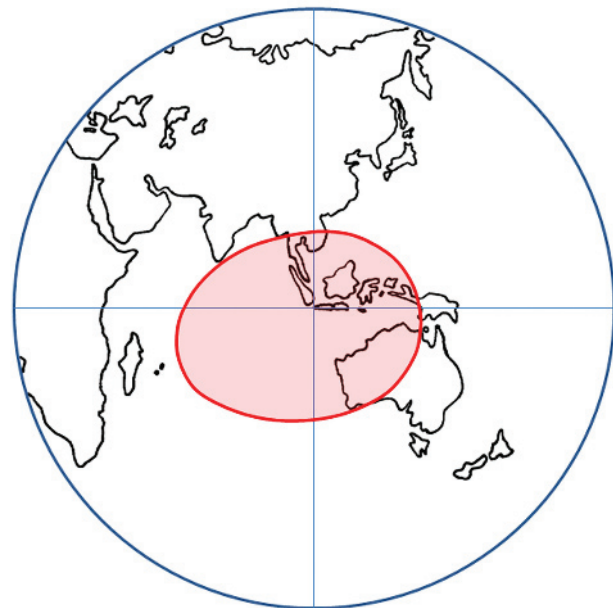


Fig. 5. An estimate of the range of audible sound from the main explosion based on reports from land observers and ships at sea. The range is shown as the red shaded area. Note the elongation toward the west. The shaded area is about 1/13th of the area of the surface of the Earth. Re-drafted from Symons, 1888.

cals to a few hundred pascals—several tenths of a percent of atmospheric pressure! The dominant period of the wave ranged from 100 to 200 minutes (Fig. 4). These periods are longer than the periods of typical vertical buoyancy oscillations in the atmosphere. A parcel of air displaced upwards

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drops in temperature as it expands. If the temperature in the surrounding air at the new height is higher than the lifted parcel's temperature, then the parcel, denser than its surroundings, will sink back down. This is the condition for vertical stability. Instability for vertical displacement creates some of the most interesting and violent weather; however, most regions of the atmosphere are stable most of the time (at least for displacement of *dry* air). When there is vertical stability, there is a natural frequency for buoyant oscillation. This frequency—the Brunt-Väisälä frequency—depends on the vertical temperature gradient; however, the corresponding oscillation period is frequently in the range from 5 to 10 minutes. Since the dominant frequencies at long range for the pressure pulse from Krakatoa are well below the Brunt-Väisälä frequency, buoyancy would have played a significant role with respect to *vertical* particle displacements.

In addition to records of the pressure wave, the Krakatoa Committee compiled reports of audible sound from the explosion (Fig. 5). Only reports from at least 30 km distant are included in the tabulation: 84 reports from land observers and 15 reports from ships' logs. There were 53 reports from greater than 1500 km and 16 reports from greater than 3000 km. The farthest credible report⁴ came from Rodrigues Island in the Indian Ocean (600 km east of Mauritius), a distance of more than 4800 km. In most cases, observers reported sounds like those of artillery or cannon fire. While many locations reported hearing sounds intermittently for hours, "...it is very remarkable that at many places in the more immediate neighborhood of the volcano they ceased to be heard soon after [the main eruption] ...although it is known that the explosions continued with great intensity for some time longer." The Committee speculates that the ejected ash may have acted to block the sound at nearby locations; however, not enough is known of the local atmospheric conditions to rule out formation of acoustic shadows by refraction.

While the linear theory and the roots of nonlinear theory were published within a decade of the Krakatoa explosion, interest in the propagation of very-low-frequency waves in the atmosphere continues to the present. A more complete understanding of the atmosphere and recognition that waves can propagate at least as high as the lower thermosphere (100 km altitude) have improved model calculations. The roles of absorption and nonlinearity especially at high altitudes are areas of current research interest. Rayleigh (among others) set the stage for the importance of nonlinearity by pointing out that, if energy is conserved in the wave front, then as the ambient density decreases, the wave particle velocity must increase (as the square-root of density). With a drop in density by a three orders of magnitude from the surface to 100 km, the acoustic Mach number will be significantly greater at extreme altitudes; consequently, nonlinearity will likely be of more importance than at low altitudes. Whatever the fate of theoretical investigations, global observation will be as important in the future as it was for understanding the Krakatoa explosion.[AT](#)

ENDNOTES

Note: The more common spelling—Krakatoa—is used in this article. When searching for further information, consider the alternate form: Krakatau.

- 1 See <http://www.ndbc.noaa.gov/>. Historical data is archived for several years. For example, select Buoy 43412 and set the start and end dates to 27 February 2010 to see the tsunami passage on the water-column height plot. The buoys with the DART II (Deep-ocean Assessment and Reporting of Tsunamis) instrumentation payload record water-column height. Buoy 51406 also shows a clear signature.
- 2 I have assembled those contours into an animation of the wave front evolution. That animation is available in the sidebar of this article.
- 3 Variations in apparent speed from measurements at different stations were considerably higher than could be accounted for by measurement uncertainty. From the text of the Krakatoa Committee report, "The probable limits of error in the estimation of the times are, in almost all cases, well within thirty minutes..."
- 4 The Committee cites an account in *Comptes Rendus* (March, 1885, Vol. c, pg. 755) of sounds heard in the Cayman Islands, 1600 km from the antipodal point: "The evidence, however, is of so indefinite a nature that it has not been inserted in the tabular statement annexed."

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