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. 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 NDBC 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 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 eruption.

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 picture 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
The Krakatoa Volcano

WAVE NO. 1.
FIRST PASSAGE FROM
KRAKATOA TO
THE ANTIPODES

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 04:00 UTC (about one hour after the main explosion) on 27 August, 1883, with the earliest contour, labeled “1”, 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 20:00 UTC 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-emanated 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, $A \cos \theta - B \cos \theta$ where $\theta$ 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 propagation 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 compression- al 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-
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neous atmosphere whose pressure through half the height of the homoge-

ty, 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 homoge-

neous 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 sur-

face-wave propagation speeds far slower than the speed of propa-

gation for compressional waves. For example, the tsunami pro-

duced 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 cen-
tury: 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 vari-
ation in the atmosphere by including a zone of stratospheric heat-
ing—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 characteris-
tic 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 dis-
tant stations on the first circuit ranged from a few tens of pas-
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 oscilla-
tions in the atmosphere. A parcel of air displaced upwards
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 distances. 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.

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.

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.”

REFERENCES


Symons, G. J. (ed.) (1888).”The eruption of Krakatoa and subsequent phenomena,” Report of the Krakatoa Committee of the Royal Society (Trübner and Co., London), 1888. Only a small part of this large volume concerns the pressure wave and sounds from Krakatoa.

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