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Infrasound events detected with the Southern California Seismic Network

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[1] We examine continuous data from the Southern California Seismic Network from 2003 and identify infrasound acoustic waves from 76 previously undetected events. Using waveform cross-correlation of the signal envelope functions, we determine their relative arrival times and estimate source locations. The waves travel at acoustic speeds of 320 m/s and are observed in seismic records up to 450 km from their probable source locations off the west coast of southern California. The dominant daylight occurrence of the events points to a man-made source related to military activity. The events are mostly recorded in the winter and spring when atmospheric conditions trap acoustic energy near the Earth's surface and favor propagation to the west. These results suggest that data from regional and global seismic networks can supplement observations from infrasound arrays for Comprehensive Test Ban Treaty monitoring and geophysical applications such as volcano monitoring, bolide detection, atmospheric acoustic sources and atmospheric tomography. **Citation:** Cochran, E. S., and P. M. Shearer (2006), Infrasound events detected with the Southern California Seismic Network, *Geophys. Res. Lett.*, *33*, L19803, doi:10.1029/2006GL026951.

1. Introduction and Background

[2] Infrasound signals propagate in the Earth's atmosphere for hundreds to thousands of kilometers and are of interest for Comprehensive Test Ban Treaty (CTBT) verification [*Drob et al.*, 2003]. Infrasound arrays are currently being installed in several regions of the world to observe man-made signals associated with missile launches and chemical explosions from mining or other activities [e.g., *Brown et al.*, 2002a; *Hagerty et al.*, 2002]. In addition, they have been used to track natural infrasound sources including earthquakes, volcanos, fireballs, meteorites and even surf from large distances [*Blanc*, 1985; *Tahira et al.*, 1996; *Brown et al.*, 2002b; *Evers and Haak*, 2003; *Arrowsmith and Hedlin*, 2005].

[3] Infrasound is defined as waves of frequencies between 0.001–20 Hz propagating in the Earth's atmosphere. For comparison, the human hearing range is 20 Hz–22 kHz. The transmission and observation of these acoustic waves are highly dependent on atmospheric conditions, including temperature, pressure and wind direction [e.g., *Brown et al.*, 2002a; *Drob et al.*, 2003]. Typically, the observed waves propagate through the lower 100 km of the Earth's atmosphere, including the troposphere, stratosphere and lower thermosphere. Atmospheric temperature inversions tend to strengthen the transmission of near-surface infrasound and observations are primarily downwind of the source, with some dependence of the measured back azimuth on wind shear [*Larom et al.*, 1997].

[4] Approximately 60 infrasound stations are installed in the International Monitoring System (IMS) infrasonic network [*Brown et al.*, 2002a]. When detected on several widely spaced infrasound arrays, the approximate location of observed events can be estimated. Infrasound arrays are currently being installed around the globe to assist in the enforcement of the Comprehensive Test Ban Treaty.

[5] Given favorable atmospheric conditions, the low frequency airwaves of a blast or bolide travel greater distances with less attenuation than the associated seismic waves. Depending upon the sensor design and its degree of isolation from the air, an above ground or near-surface seismic station potentially will record both seismic waves and the ground movements induced by pressure changes from passing airwaves, and may also record the pressure fluctuations directly. Broad-band seismometers, sensitive to frequencies between 0.01–20 Hz, span a similar frequency range as typical infrasound sensors, but are currently deployed much more widely. Thus, if atmospheric pressure waves can be detected by these seismic stations, the infrasound community would benefit from increased data and would be able to improve detection and location of acoustic sources. Here, we show that acoustic waves are recorded on the dense Southern California Seismic Network (SCSN) and we use the timing of these arrivals to constrain the location and probable origin of regional infrasound sources.

2. Data Processing

[6] Over 200 seismic stations in southern California have recorded data continuously since 2003; the data are processed and archived by the Southern California Seismic Network (SCSN) and are made available by the Southern California Earthquake Data Center (SCEDC). The stations are spread across southern California with the highest density of stations concentrated in the Los Angeles basin. Data are recorded at 40–100 samples per second by broad-band sensors, usually Streckeisen STS-2. The seismic station set-up varies depending on location, but typically consists of a sensor placed on a concrete pad either above ground or in a shallow vault. Data are recorded on-site and also transmitted to SCSN for rapid earthquake determination and archiving.

[7] We search the data recorded by the SCSN in 2003 for infrasound signals. To highlight infrasound events, we apply a bandpass filter between 1–10 Hz and compute the root mean square (RMS) amplitude of the seismic records to obtain an envelope of the data. For rapid examination of

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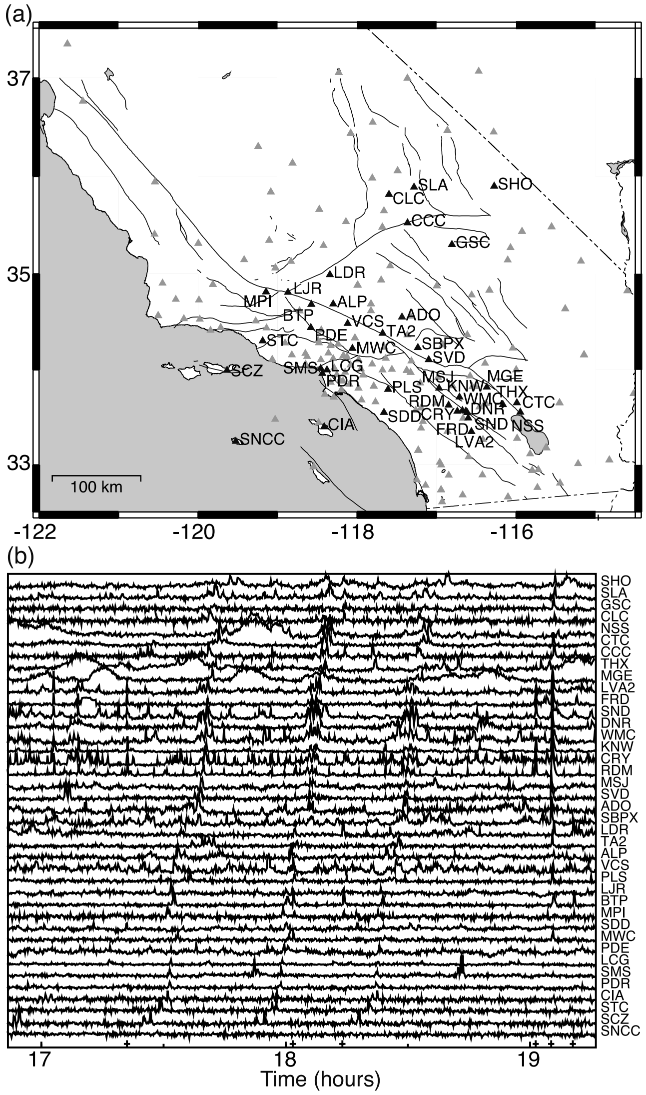

Figure 1. (a) Map of Southern California Seismic Network (SCSN) continuously recording seismic stations. Black labeled triangles are stations for which data are plotted in Figure 1b. (b) Root mean squared (RMS) horizontal trace of three infrasound events on day 046 in 2003 recorded between hours 17–19 UTC. Only the east-west component is shown and traces are band-passed between 1–10 Hz. Traces are ordered roughly by signal arrival time, or distance from the source, and station names are given on the right.

the large volume of data, the resulting time series are averaged and down-sampled to 0.1 samples per second. With the above processing, the data volume is significantly reduced in size from 13 Mb to 36 Kb per station per day. This makes possible the rapid visual scanning of the seismic data for evidence of infrasound events present across multiple stations. These events are not identified in the SCSN catalog, presumably because of their slow propagation velocities compared to earthquake signals and their often emergent onsets. For candidate signals, we perform cross-correlation of the RMS records to approximately locate the source of the incoming acoustic wave and estimate the velocity of the propagating wave. Given the source location, signal characteristics, and temporal distribution we can establish the likely cause of the infrasound signals recorded by the SCSN.

3. Infrasound Events in Southern California

[8] We examine the infrasound events recorded by the SCSN in 2003 and use arrival times to determine their possible source locations. The acoustic signals have significant amplitudes over large distances and are typically recorded at stations up to 400 km from the source, which allows us to detail the changing characteristics of the wave and also gives us a wide range of stations with which to locate the source. In addition, we detail the number and distribution of the infrasound events from 2003 for which we have clear records.

[9] During 2003, we observe 76 infrasound events originating off the west coast of southern California. Each infrasound event is recorded by at least 10 network stations and can be clearly identified on the root-mean-squared (RMS) records. The distribution of seismic stations in southern California is shown in Figure 1a. RMS traces of the east-west horizontal components for 39 seismic stations are shown in Figure 1b. The RMS traces show acoustic waves from three separate sources that arrive between UTC hours 17–19 on February 15, 2003, with multiple pulses observed for stations with longer propagation paths.

3.1. Signal Characteristics

[10] Figure 2 shows the raw seismic data for 5 stations high-pass filtered at 9 Hz. The top trace is recorded by station SNCC located on San Nicolas Island (Figure 1a) and the other traces are at distances ranging from 100–400 km from SNCC. The higher frequency content and more impulsive signal on San Nicolas Island likely indicate a nearby source. Note that for station SNCC no signal is observed on the RMS trace that is filtered between 1 and 9 Hz (Figure 1b).

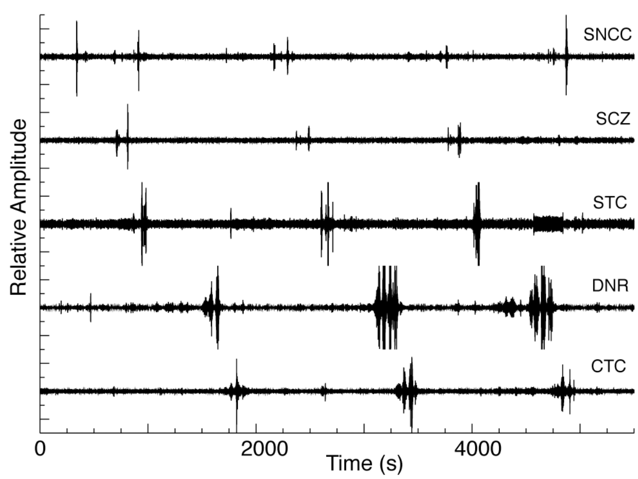

Figure 2. Horizontal component (east-west) of the seismic trace shown for a subset of stations (SNCC, SCZ, STC, DNR, and CTC). The traces indicate the changing character of the signal as a function of distance from the source. Waveforms are high pass filtered above 9 Hz.

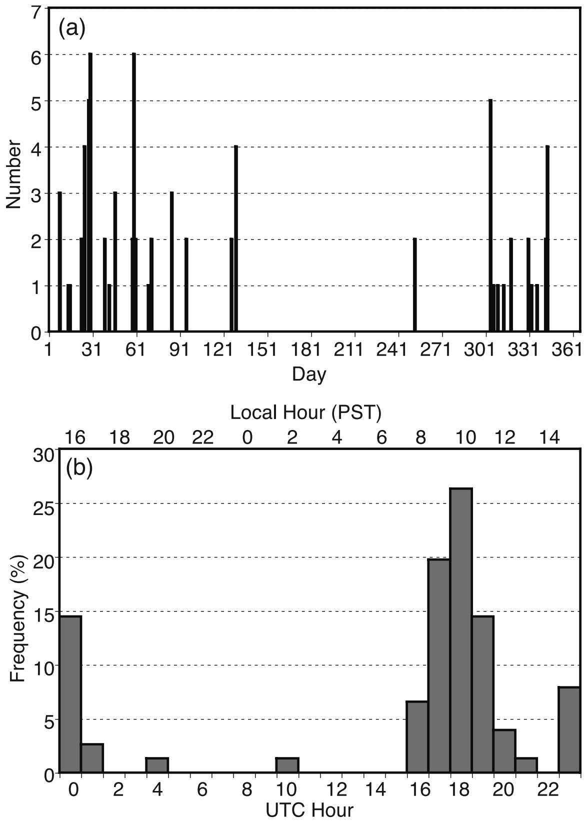

Figure 3. (a) Histogram of the number of infrasound sources per day in 2003 that were observed on at least 20 seismic stations. (b) Histogram of the distribution of events over a 24 hour period for all signals observed in 2003. Note the high number of observations between UTC 1600–2000.

[11] As noted above, there is a clear change in the character of the acoustic wave with distance. Records at larger distances have multiple arrivals from the same event. For example, as shown in Figure 2, station DNR at the mid-distance range of 200 km from SNCC has 4 to 5 clear pulses. In contrast, station SCZ with the earliest observed RMS arrival time has only one or possibly two pulses. Multiple pressure pulses are likely due to multipathing and ducting at different heights in the Earth's atmosphere [*Drob et al.*, 2003]. In principle, these data could be used to map details of the atmospheric velocity structure, but given our limited distribution of sources we do not attempt this here.

3.2. Distribution of the Events

[12] The acoustic events exhibit clear seasonal and daily patterns in their occurrence times (Figure 3). A larger portion of the events are observed during the fall and winter months from November until April with only two events observed in the summer of 2003. Since it is likely that the source of the infrasound signals is continuous throughout the year, the seasonal distribution suggests that the events are only detected when atmospheric conditions favor propagation to the east, toward the seismic network. *Arrowsmith and Hedlin* [2005] show similar seasonal variations for infrasound induced by surf hitting the coast of southern California.

[13] The distribution over a 24-hour period shows the acoustic events are preferentially detected between UTC hours 1600 to 2000 (local time 0800–1200) with a second, lesser peak around 2400 (Figure 3b). The predominance of events between local time 0800–1200 suggests the signals are man-made as such a well-defined peak would be surprising from a natural source. *Arrowsmith and Hedlin* [2005] do not note a significant daily variation in signal return from their study of surf in southern California. In contrast, *Le Pichon et al.* [2005] note a diurnal variation in detection levels for volcano-generated infrasound in the southwest Pacific due to daily variations in wind-related noise. They observe fewer events during daylight hours over a roughly 12 hour period as wind speeds and wind-noise increases. Our events are preferentially detected during the local morning hours during a narrow 4 hour window. Wind speeds in southern California generally increase during the late morning hours and drop again soon after sunset; therefore, the daily variation in detection that we observe is unlikely to be controlled by wind speed alone.

3.3. Locating the Infrasound

[14] We cross-correlate the RMS traces to estimate arrival times and approximately locate the infrasound sources. Note that cross-correlating the signals is not exact due to the changing character of the propagating wave; however, it provides a simple way to rapidly estimate the relative timing of the acoustic waves. Cross-correlating finds the best match to the overall shape of the signal envelope rather than the first arrival. Picking the arrivals from the raw seismic data is prohibitively difficult due to the emergent nature and multiple pulses common in these sound signals, especially at large distances.

[15] To determine a best-fit source location for each observed infrasound signal, we analyze a set of possible locations using a grid search over latitudes between 25°N and 45°N and longitudes between 130°W and 110°W. The spatial step size in both latitude and longitude is 0.1 degrees. The source is assumed to be at the Earth's surface, so no adjustment is made for source or station elevation. The latitude and longitude that minimizes the residuals for a given set of arrival times is taken as the best fit source location. The propagation velocity is determined by the linear fit to travel time versus distance for the arrivals and is not predetermined other than it is required to be positive. We find that the average best-fitting velocity for signals recorded by at least 15 stations is approximately 320 m/s, a typical acoustic speed for infrasound propagating in the near-surface region [*Drob et al.*, 2003].

[16] Our location method assumes a point source rather than a moving source, such as a sonic boom from an aircraft. *Mori and Kanamori* [1991] observed shock waves from sonic booms recorded by the southern California seismic network in 1989–90 that exhibit a clear N-wave, or pressure wave that is characteristic of sonic booms. Our data do not clearly show N-wave pulses or the hyberbolic arrival time pattern characteristic of sonic booms, so we do not consider moving sources here.

[17] In order to estimate uncertainties in the source locations, we use the chi-squared method to estimate the 95% confidence ellipses. We limit the number of free parameters for each event by imposing a propagation velocity of 320 m/s.

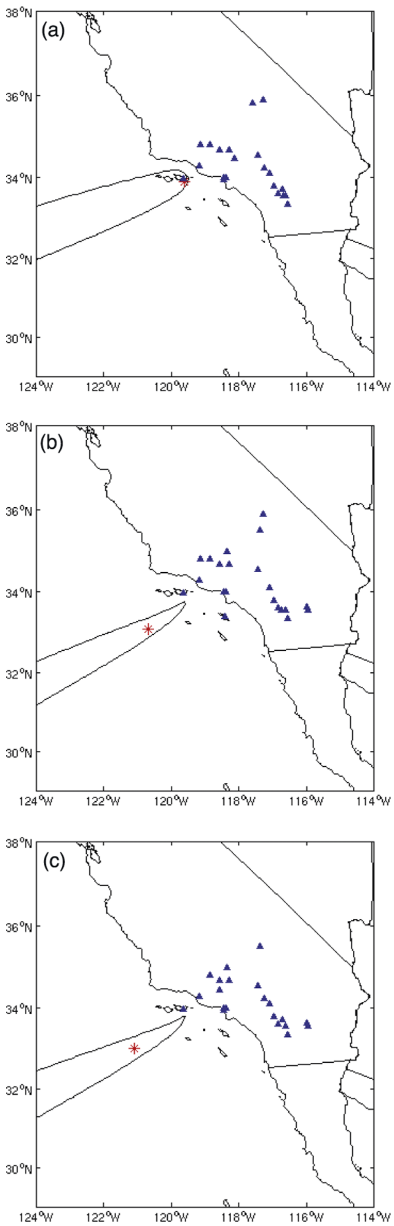

Figure 4. Best fit source locations for the 3 signals shown in Figure 1b on day 046 in 2003. The stars give the best fits for the available data. Each ellipse gives the 95% confidence interval, as explained in the text. Note that the fits are not well determined as all of the stations fall to the west of the source, but each signal shows a similar back azimuth.

Figure 4 shows the best fit to estimated arrivals for each of the three sources shown in Figure 1b. The infrasound source originates from the west and the best fits to signals A and B indicate a possible origin near the Channel Islands located 50–100 km off the coast of southern California. The best fit to signal C arrivals puts the source location slightly farther to the southwest. However, for these three signals, there is little difference in the 95% confidence ellipses suggesting the signals may have originated from approximately the same location.

[18] The best-fit locations for 26 of the best-recorded acoustic signals in 2003 are shown in Figure 5. Results are only shown for the signals that are recorded by at least 15 stations and with cross-correlation values greater than 0.6. The source of the infrasound is off the west coast of California, near the Channel Islands. However, it is important to note that the distances of the source locations from the coast are not well-constrained because most of the seismic stations are located to the west of the source. Examples of typical error ellipses are shown in Figure 4.

3.4. Man-Made or Natural?

[19] The physical cause of the infrasound signals is not simple to deduce due to the source locations outside of the main southern California seismic network. We use the timing and origin of the infrasound to determine whether the signal is likely natural or man-made. As stated above, the timing of the observed infrasound signals is highly non-random with most of the events recorded between 1600–2000 UTC, or 0800–1200 local time. It is unlikely that a natural source of the infrasound, such as lightning or bolides, would be so regularly distributed.

[20] In addition, the location of the infrasound is in an area of known military activity. As shown above, the infrasound sources originate off the west coast of California, near the offshore islands. Several of these islands, specifically San Nicolas and San Clemente, as well as a large portion of the surrounding ocean, known as Warning Area 291, are used for live-fire military training. It is therefore likely that the infrasound signals are due to military-related activities. The strength of the signals is somewhat surprising given the distance of many of the seismic stations from this location. However, a very early study by *Gutenberg and Richter* [1931] showed similar observations of navy gunfire off the coast of California causing disturbances, including rattling of windows and doors, up to 300 km away; although no

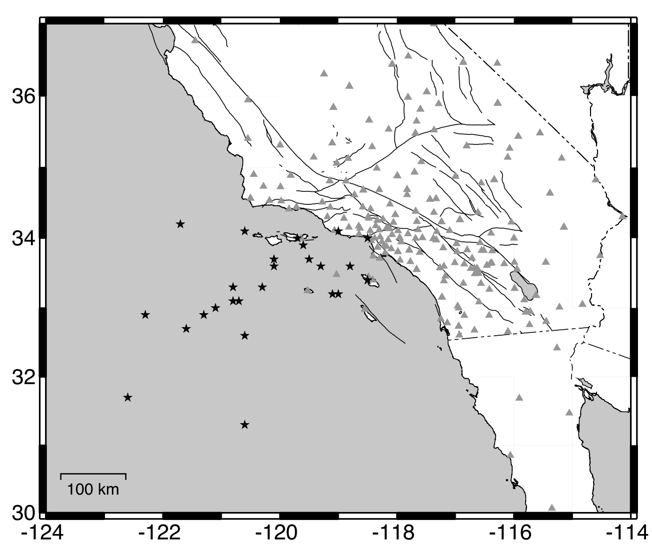

Figure 5. Best fit source locations (stars) for the 26 infrasound signals recorded in 2003 recorded by at least 15 stations and with cross-correlation values above 0.6. Note that the errors for these locations are similar to those shown in Figure 4.

associated signals were observed on the Pasadena seismic station, one of the few operating in 1930.

4. Discussion

[21] We use the southern California seismic network data to examine the number, origin, and source of regional infrasound signals. During 2003, we observe 76 clear acoustic signals that propagate across the region during the winter and spring months when atmospheric conditions favor near-surface propagation toward the seismic network [*Arrowsmith and Hedlin*, 2005]. While we can not definitively determine the physical source of the infrasound, the timing and location suggest that the signals are likely man-made.

[22] The high amplitude of the acoustic waves on the seismometers and clear observations up to 450 km from the origin were not expected. Further work is needed to determine whether the seismic instruments are responding to direct pressure waves, or from ground excitation due to the passing acoustic waves. Using a seismic record of a shuttle reentry, *Kanamori et al.* [1991] estimated the response of a half space from pressure changes induced by a passing shock front and found good agreement with direct pressure measurements made during earlier missions. Observations from co-sited pressure sensors and seismometers are needed to definitively resolve the mechanism by which the seismometers are recording the infrasound and to determine the relative sensitivity of seismic versus acoustic instruments to infrasound signals; it is expected that the acoustic instruments are better suited to record low-level signals.

[23] It is clear from the results presented above that seismic network data can be of great value for detecting and locating infrasound signals. While infrasound arrays have the advantage of quick determination of an event back azimuth that is independent of travel time calculations, the dense station spacing in southern California may allow for more detailed mapping of atmospheric propagation than can be obtained from the available infrasound arrays. Data from regional and global seismic networks could be used in conjunction with current infrasound networks for Comprehensive Test Ban Treaty monitoring, volcano hazard monitoring, bolide detection and other geophysical applications.

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References

Arrowsmith, S. J., and M. A. H. Hedlin (2005), Observations of infrasound from surf in southern California, *Geophys. Res. Lett.*, *32*, L09810, doi:10.1029/2005GL022761.

Blanc, E. (1985), Observations in the upper-atmosphere of infrasonic waves from natural or artificial sources—A summary, *Ann. Geophys.*, *3*, 673–687.

Brown, D. J., C. N. Katz, R. L. Bras, M. P. Flanagan, J. Wang, and A. K. Gault (2002a), Infrasonic signal detection and source location at the Prototype International Data Centre, *Pure Appl. Geophys.*, *159*, 1081–1125.

Brown, P. G., R. W. Whitaker, D. O. ReVelle, and E. Tagliaferri (2002b), Multi-station infrasonic observations of two large bolides: Signal interpretation and implications for monitoring of atmospheric explosions, *Geophys. Res. Lett.*, *29*(13), 1636, doi:10.1029/2001GL013778.

Drob, D. P., J. M. Picone, and M. Garcés (2003), Global morphology of infrasound propagation, *J. Geophys. Res.*, *108*(D21), 4680, doi:10.1029/2002JD003307.

Evers, L. G., and H. W. Haak (2003), Tracing a meteoric trajectory with infrasound, *Geophys. Res. Lett.*, *30*(24), 2246, doi:10.1029/2003GL017947.

Gutenberg, B., and C. Richter (1931), Psuedoseisms caused by abnormal audibility of gunfire in California, *G. Beitr. Geophys.*, *31*, 155–157.

Hagerty, M. T., W. Y. Kim, and P. Martysevich (2002), Infrasound detection of large mining blasts in Kazakstan, *Pure Appl. Geophys.*, *159*, 1063–1079.

Kanamori, H., J. Mori, D. L. Anderson, and T. H. Heaton (1991), Seismic excitation by the space-shuttle Columbia, *Nature*, *349*, 781–782.

Larom, D., M. Garstang, K. Payne, R. Raspet, and M. Lindeque (1997), The influence of surface atmospheric conditions on the range and area reached by animal vocalizations, *J. Exp. Biol.*, *200*, 421–431.

Le Pichon, A., E. Blanc, D. Drob, S. Lambotte, J. X. Dessa, M. Lardy, P. Bani, and S. Vergniolle (2005), Infrasound monitoring of volcanoes to probe high-altitude winds, *J. Geophys. Res.*, *110*, D13106, doi:10.1029/2004JD005587.

Mori, J., and H. Kanamori (1991), Estimating trajectories of supersonic objects using arrival times of sonic booms, *U.S. Geol. Surv. Open File Rep., 91-48*, 15 pp.

Tahira, M., M. Nomura, Y. Sawada, and K. Kamo (1996), Infrasonic and acoustic-gravity waves generated by the Mount Pinatubo eruption of June 15, 1991, in *Mud and Fire*, edited by C. G. Newhall and R. S. Punongbayan, pp. 601–613, U.S. Geol. Surv., Boulder, Colo.

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