Detecting hidden volcanic explosions from Mt. Cleveland Volcano, Alaska with infrasound and ground-coupled airwaves

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Received 21 August 2012; revised 8 October 2012; accepted 9 October 2012; published 13 November 2012.

[1] In Alaska, where many active volcanoes exist without ground-based instrumentation, the use of techniques suitable for distant monitoring is pivotal. In this study we report regional-scale seismic and infrasound observations of volcanic activity at Mt. Cleveland between December 2011 and August 2012. During this period, twenty explosions were detected by infrasound sensors as far away as 1827 km from the active vent, and ground-coupled acoustic waves were recorded at seismic stations across the Aleutian Arc. Several events resulting from the explosive disruption of small lava domes within the summit crater were confirmed by analysis of satellite remote sensing data. However, many explosions eluded initial, automated, analyses of satellite data due to poor weather conditions. Infrasound and seismic monitoring provided effective means for detecting these hidden events. We present results from the implementation of automatic infrasound and seismo-acoustic eruption detection algorithms, and review the challenges of real-time volcano monitoring operations in remote regions. We also model acoustic propagation in the Northern Pacific, showing how tropospheric ducting effects allow infrasound to travel long distances across the Aleutian Arc. The successful results of our investigation provide motivation for expanded efforts in infrasound monitoring across the Aleutians and contribute to our knowledge of the number and style of Vulcanian eruptions at Mt. Cleveland. Citation: De Angelis, S., D. Fee, M. Haney, and D. Schneider (2012), Detecting hidden volcanic explosions from Mt. Cleveland Volcano, Alaska with infrasound and ground-coupled airwaves, Geophys. Res. Lett., 39, L21312, doi:10.1029/2012GL053635.

1. Introduction

[2] On many volcanoes data are routinely collected on-site by means of ground-based instrumentation and broadcast to volcano observatories in real-time. Seismic networks represent the backbone of real-time monitoring systems as magma migration is frequently accompanied by measurable earthquake activity, and the onset of eruptions is characterized by distinctive seismic signatures. Although seismometers are capable of identifying even minor changes accompanying magmatic unrest, their ability to detect ground motion associated with volcanic activity reduces rapidly with distance from the source. Due to strong attenuation effects, and the relatively small energy radiated by volcanic earthquake sources, seismic installations are more effective at close range, within about 20 km of the volcanic edifice. Large explosions, with Volcanic Explosivity Index (VEI) [Newhall and Self, 1982] of 4 or greater have been recorded at relatively large distances (up to about 400 km) from the vent [e.g., Prejean and Brodsky, 2011]. In contrast, smaller eruptions, with VEI less than 3, are unlikely to be detected by seismometers more than a few kilometers away from the source.

[3] In remote locations such as the Aleutian Islands of Alaska, where access is costly and difficult, on-site monitoring may not be realistic and volcanic surveillance often relies on alternative methods such as satellite remote sensing. Satellite remote sensing at mid and thermal infrared wavelengths (3.5 to 12 μm), provides indications on the radiant temperature of volcanoes and detection of ash-rich volcanic clouds. The thermal infrared brightness temperature difference (BTD) technique is commonly used to detect and track ash-rich volcanic clouds [Prata, 1989]. The magnitude of the ash signal is dependent upon the abundance of fine-grained volcanic ash, the temperature contrast between the volcanic cloud and the underlying surface, and the relative abundance of water within the volcanic cloud. Short-duration, low-altitude volcanic clouds generated by eruptive processes that do not produce abundant fine-grained ash are difficult to detect with this technique. Meteorological cloud cover can also obscure low-altitude eruption plumes, thus preventing their detection by satellite methods.

[4] In recent years, several studies have investigated long-range infrasound from large volcanic eruptions, at distances of hundreds of km, or greater, from the source [e.g., Fee et al., 2011; Matoza et al., 2011a, 2011b; Dabrowa et al., 2011]. The infrasound generated by sizeable volcanic explosions can travel up to thermospheric altitudes (>80 km), where its propagation over large distances is controlled by atmospheric winds and temperature. Large explosive events such as the eruptions of Kasatochi (2008) and Okmok (2008) volcanoes in Alaska, USA, have been detected by infrasound sensors located as far away as 4400 and 5200 km from the source, respectively [Fee et al., 2010]; the 2005 eruption of Manam volcano, Papua New Guinea, was recorded at a striking 10,673 km from the vent by the International Monitoring System I33MG array in Madagascar [Dabrowa et al., 2011].

[5] In this manuscript we discuss how the combined use of regional- (15–250 km) and global-scale (>250 km) infrasound and seismic data led to the discovery of many...
“hidden” explosions from Mt. Cleveland, Alaska, whose plumes were not detected in satellite data due to cloud cover. We show that atmospheric conditions across the Aleutian Arc support long-range, east-to-west, acoustic propagation as far away as many hundreds of km from Mt. Cleveland via tropospheric ducting of sound. We report observations of infrasound and ground-coupled acoustic waves across the Aleutian Arc and Western Alaska. Finally, we discuss how these observations were employed to implement automated alarm systems and dispatch warnings of volcanic activity at Mt. Cleveland.

2. Background

[6] Mt. Cleveland (1730 m) is a stratovolcano situated on the western half of Chuginadak Island, about 40 km west of Umnak, in the Aleutian Islands of Alaska (Figure 1) [Miller et al., 1998]. Activity at Mt. Cleveland is monitored primarily using remote sensing data from frequent coarse spatial resolution meteorological satellites. There is no real-time, local, seismic network on the volcano; the closest seismic site is located about 75 km to the east.

[7] Mt. Cleveland is one of the most active volcanoes in the Aleutians; eruptions producing ash to altitudes in excess of 10 km above sea level (asl) occurred in 1997 and 2001. At least 10 smaller, low-altitude (<6 km asl) ash eruptions have been detected in satellite images since 2001. The eruptive activity that began in late July 2011 marked a change in the typical eruptive pattern of the previous 10 years, and was characterized by slow extrusion of a lava dome/plug in the summit crater. Lava extrusion continued through mid-October 2011, at which point a small dome occupied the summit crater (about 500,000 m³). This first dome was destroyed by explosions in late December 2011. No fewer than five other domes were observed throughout 2012, although less voluminous (<50,000 m³) than the first. Some of the explosions described in this paper, however, occurred when no lava was observed to have occupied the summit crater (see auxiliary material, Table S1).1

3. Distant Monitoring of Mt. Cleveland: Data and Methods

[8] During late 2011 volcanic activity at Mt. Cleveland began to intensify; the Alaska Volcano Observatory (AVO) detected explosive events, some resulting in the destruction of small lava domes within the summit crater and generating ash clouds to altitudes of ~7–8 km asl. The signals associated with eruptive activity at Mt. Cleveland typically registered on seismometers across the Aleutian Arc with apparent velocities of 320–350 m/s. The extremely slow velocity (about 1 order of magnitude smaller than typical seismic velocity in the crust) suggests that these waves did not reflect propagating ground motion directly associated with eruptive activity. Such low velocities, typical of sound propagation in the lower atmosphere, indicated coupling at eruptive activity. Such low velocities, typical of sound reflecting propagating ground motion directly associated with eruption. The acoustic waves generated by a volcanic explosion impinge on the Earth’s surface and are recorded by seismometers [McNutt, 1986; Johnson and Malone, 2007]. Essentially, ground motion is generated via direct loading of the surface from the atmospheric pressure field associated with the acoustic wave field [Ben-Menahem and Singh, 1981].

[9] The local seismic network operated by AVO on Okmok volcano, about 120 km from Mt. Cleveland, proved particularly effective in recording ground-coupled acoustic signals. An example, recorded on 29 December 2011, is shown in Figure 1b. In order to detect ground-coupled airwaves in real-time, we implemented an automatic acoustic phase associator for the Okmok network, similar to automatic waveform scanning algorithms employed to detect ordinary earthquakes. The algorithm checks whether candidate signals recorded at multiple sites exhibit expected time delays for an airwave from Mt. Cleveland. Walker et al. [2011] have used reverse-time migration (RTM) to detect ground-coupled airwaves on the USAarray in the Western United States. RTM works well with an extensive network such as the USAarray, which consists of approximately 400 stations. Since the Okmok network in the Aleutian Islands is considerably smaller (11 stations at full operational capacity), we designed an alternative, simpler, detection algorithm. Candidate signals are identified using a short-term-average/long-term-average (STA/LTA) filter [Allen, 1978]. For each detected arrival within a 2-minute time window, we reduce the arrival time at a station by the expected differential travel-time between that site and the station closest to Mt. Cleveland. Theoretical differential travel-times are derived assuming a uniform apparent moveout velocity of 340 m/s, although variations of up to +/−30 m/s around this mean value (310–370 m/s) are acceptable. This range of apparent velocities covers the possibilities for tropospheric arrivals expected at Okmok. Once reduced, the times of the picks should be equal to each other if the event is an airwave propagating from Mt. Cleveland, and the assumed moveout velocity is correct. In practice, because of atmospheric variability and uncertainty in the picking, the reduced arrival-times, although close, are not equal to each other. We define a tolerance for the detection of acoustic arrival times by allowing the reduced picks to have a standard deviation of up to +/−6 s. This time delay can be expressed in terms of an apparent velocity variation by using the perturbational relationship $\Delta v/v = (+−)\Delta \tau/\tau$ [Poupinet et al., 1984], where $v$ is the apparent velocity, $\tau$ is the differential travel-time between the closest and furthest stations, $\Delta \tau$ is the standard deviation, and $\Delta v$ is the associated change in apparent velocity. Using $v = 340$ m/s and $\tau = 70$ s (the travel time between stations OKSP and OKER in Figure 1b), we obtain the aforementioned $\Delta v = (+−)30$ m/s.

[10] The recent installation of infrasound sensors across the Aleutians (Figure 1a) has considerably augmented AVO’s ability to detect explosive activity from Mt. Cleveland and other volcanoes. AVO currently operates infrasound sensors at 8 sites in the region (Figure 1a). In addition, the University of Alaska Fairbanks (UAF) operates an 8-element infrasound array (ISS53), and a six-element infrasound array (ISS53) in Fairbanks, AK, and a six-element infrasound array in Southwestern Alaska near Dillingham (DLL) (Figure 1a). ISS53 and DLL both use Chaparral Physics Model 50 sensors (flat response 0.02–50 Hz), and have low background noise levels compared to the Aleutian Arc sites. Between 12 December,

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1Auxiliary materials are available in the HTML. doi:10.1029/2012GL053635.
Figure 1. (a) Locations of Mt. Cleveland (red triangle) and infrasound stations in Alaska. Black dots are individual infrasound sensors, yellow dots are infrasound arrays. The inset shows the Okmok seismic network. (b) Record section of Mt. Cleveland explosion on 29 December 2011 from the Okmok network. For reference, the gray dashed line displays propagation at 335 m/s across the network. The first 6 traces are seismograms, the bottom trace is an infrasound record.
algorithm filters data between 0.5–DLL, we implemented an automatic detection system. The eruption signals from Mt. Cleveland are often obvious at 0.25 waveforms for signals with an acoustic trace velocity of 2011 explosion is shown in Figure 2. The signal at DLL lasts detection parameter. The DLL record of the 29 December

Figure 2. DLL infrasound array detection of the Mt. Cleveland explosion on 29 December 2011. (a) 0.1-5 Hz delay-and-summed, beamformed waveforms. The (b) trace velocity and (c) back-azimuth data segments are colored by the Fisher statistic. The infrasound from Cleveland arrives at ~1404 UTC with a high Fisher statistic, an acoustic trace velocity (~0.33 km/s), and a back-azimuth similar to the theoretical azimuth to the volcano (dotted line).

2011, and 17 August, 2012, 20 explosive events from Mt. Cleveland were detected by the infrasound instrumentation (see Table S1).

[11] Standard infrasound array processing techniques [Fee et al., 2011] are used to detect signals at DLL. Infrasound data are parsed into 30 second windows with 80% overlap with the propagation velocity across the array (trace velocity) and back-azimuth to the source determined using the least squares approach of Szuberla and Olson [2004]. The Fisher Statistic [Melton and Bailey, 1957] is then used as the detection parameter. The DLL record of the 29 December 2011 explosion is shown in Figure 2. The signal at DLL lasts ~2 min and peaks at 1.02 Pa, clearly above background. As eruption signals from Mt. Cleveland are often obvious at DLL, we implemented an automatic detection system. The algorithm filters data between 0.5–5 Hz and scans the waveforms for signals with an acoustic trace velocity of 0.25–0.45 km/s, Fisher Statistic greater than 4, back-azimuth within ±15° of the volcano, and duration >30 sec. Following the detection of the explosion on 29 December 2011, we performed retrospective analyses searching for both ground-coupled arrivals and coherent infrasound array signals, which revealed two smaller events 4 days earlier. The amplitude of these explosions at the DLL array was about half the amplitude of the event on 29 December. These earlier events had not been detected during routine remote sensing satellite checks due to a thick cloud deck over the volcano.

4. Acoustic Propagation Modeling

[12] The ability to detect acoustic phases associated with small-to-intermediate size volcanic explosions at regional-scale distances depends critically on atmospheric conditions. In order to assess the potential for distant infrasonic monitoring of Mt. Cleveland, we characterized long-range infrasonic propagation across the Aleutian Arc by means of ray tracing and parabolic equation (PE) modeling. Ray tracing is used to visualize sound propagation paths and estimate travel times. The method employed here is a range-dependent 2.5-D approximation of the full classical Hamilton ray tracing equations found in Gossard and Hooke [1975]. The eigenvector method that we use selects only rays connecting the source and receiver. The PE simulation is a wide-angle, sound-speed-insensitive approximation included in the InfraMap package [Gibson and Norris, 2002], and calculates accumulated signal loss (i.e., transmission loss) at a single frequency (0.5 Hz here) as a function of range and elevation. Atmospheric specifications are obtained from the global G2S models [Drob et al., 2003], commonly used in global infrasound studies.

[13] It is well-established that long-range infrasonic propagation is anisotropic due to strong wind jets in the atmosphere, which direct the sound downwind [e.g., Le Pichon et al., 2009]. Figure 3 displays the wind and sound speed profiles above Mt. Cleveland at the time of the 29 December 2011, explosion discussed previously. The winds (Figure 3a) are characterized by easterly jets at elevations of ~15 and 75 km, and a westerly jet at ~50 km in the stratosphere. The easterly wind jet at 15 km corresponds to the well-known jet stream, which has been shown responsible for significant tropospheric ducting of infrasound at long ranges [e.g., Drob et al., 2003]. There is also a significant northerly component to the jet stream. The reader should note that winds in the stratosphere (~15–50 km height) during this time of year are predominantly easterly, and the westerly stratospheric wind jet here is somewhat unusual. We speculate that it may have been caused by a Sudden Stratospheric Warming event [e.g., Evers and Siegmund, 2009] where stratospheric winds weaken and sometimes reverse directions during winter. Ray tracing and PE modeling (Figure 3c) from Cleveland to DLL on 29 December 2011, reflects these wind jets. A tropospheric duct between 0–20 km strongly guides sound, as suggested by rays propagating in the region and the low transmission loss. The tropospheric duct also explains why acoustic phases are clearly detected by the Okmok network at ~110–150 km distance, typically lying in an acoustic “shadow zone”. Predicted travel time to DLL for these arrivals is ~3170–3183 s, which corresponds to an expected arrival time of ~14:05 UTC, consistent with observations. Sound is also ducted at higher altitudes, but with longer propagation paths and lower amplitudes.

5. Concluding Remarks

[14] New observations and the results of preliminary modeling presented in this study demonstrate the exceptional potential for acoustic propagation across Alaska, which provides ideal conditions to implement and test
volcano monitoring systems based on distant infrasound and seismo-acoustic measurements. Numerous explosions from Mt. Cleveland were detected during 2011–2012 by seismic and infrasound sensors across Alaska. Seismo-acoustic coupling of infrasonic phases generated by explosive volcanic activity was exploited to detect eruptive events. We demonstrated that, with a latency of about 50 minutes, regional-scale infrasonic array measurements provide robust means of detection of volcanic explosions from Mt. Cleveland. Eruption detection based on ground-coupled acoustic phases recorded on Okmok provided more timely warnings, as the seismic network is located in relatively close proximity to Mt. Cleveland. However, volcano monitoring efforts should not rely primarily on second-order phenomena such as air-to-ground coupling. We encourage acoustic propagation modeling efforts to help planning future infrasonic array deployments. Ideally, a network of infrasonic arrays, which would provide a direct measurement of the acoustic wavefield, can be installed in strategic locations across the Aleutians and Alaska to provide more timely warnings of the onset of volcanic eruptions.

Acknowledgments. The authors wish to thank Rob Drob for the G2S models and ray tracing code. The authors wish to thank J.B. Johnson and an anonymous reviewer for their comments, which improved the paper. Funding for David Fee was provided by the Geophysical Institute and the National Oceanic and Atmospheric Administration under Specific Cooperative Agreement NA08NWS4680044. The opinions expressed herein are those of the authors and do not necessarily reflect the views of the National Oceanic and Atmospheric Administration.

References


Figure 3. G2S atmospheric specifications and acoustic propagation modeling from Mt. Cleveland to DLL on 29 December 2011 1200 UTC. (a) Zonal (red), meridional (blue), and along-path (black) winds are characterized by an easterly wind jet at ~20 km and westerly wind jet at ~60 km. (b) Sound speed (solid line) and effective sound speed (dotted line), with the solid vertical line representing the sound speed at the source. (c) 0.5 Hz PE modeling and ray tracing show rays and sound are primarily guided in the troposphere at 15–20 km and the thermosphere at ~120 km. Transmission loss (TL) is the accumulated loss in amplitude predicted by the PE, where warmer colors indicate lower transmission loss or higher amplitudes.

