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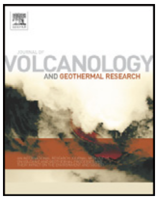

Review

An overview of volcano infrasound: From hawaiian to plinian, local to global

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ABSTRACT

Volcano infrasound is an increasingly useful technique for detecting, locating, characterizing, and quantifying eruptive activity, and can be used to constrain eruption source parameters. In recent years, studies of infrasound data from active volcanoes have shown clear progress towards mitigating volcanic hazards and understanding volcanic source processes. Volcano acoustic sources are shallow or aerial, thus volcano infrasound data provide valuable information on eruption dynamics and are readily combined with direct and remote observations of gas, ash, and other eruptive phenomena. The infrasound signals produced by volcanoes are indicative of the eruption style and dynamics. Here we review the diversity of infrasound signals generated by a wide variety of volcanic eruptions, from hawaiian to plinian, and the physical processes inferred to produce them. We place particular emphasis on regional (15–250 km distance) and global (>250 km distance) volcano infrasound studies, as recent work in this area has made significant advances in monitoring and characterizing remote and difficult-to-monitor eruptions. Long-range infrasonic detection of explosive volcanic eruptions is possible due to the energetic source mechanisms involved, minor atmospheric attenuation at low frequencies, and the existence of waveguides in the atmosphere. However, accurate characterization of the atmosphere and its spatio-temporal variability is required for reliable long-range sound propagation modeling and correct interpretation of global infrasound recordings. Conversely, because volcanic explosions are energetic and sometimes repetitive infrasound sources, they can be used to validate atmospheric and acoustic propagation models.

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1. Introduction

It is well-established that volcanoes are prodigious sources of infrasound, defined as acoustic, or sound, waves below 20 Hz. As magma rises within the earth, pressure oscillations are created from various fluid-dynamic, thermodynamic, and elastodynamic processes. These oscillations couple into the ground in the form of seismic energy, and energy from shallow sources may propagate into the atmosphere in the form of acoustic energy. In particular, the shallow exsolution and release of volcanic gases produces extensive atmospheric perturbations including short-duration, impulsive bursts (explosions) and long-duration vibrations (tremor). Lava dome collapses, Pyroclastic Density Currents (PDCs), and rockfalls generate infrasound. Aerial volcanic processes, such as volcanic jets and plumes, can produce significant acoustic energy. Quantification of volcano acoustics therefore provides information on shallow processes within the conduit and hydrothermal system as well as above the vent. The infrasound source location is also noteworthy in that it permits comparison with direct and remote observations of gas, ash, and other eruptive phenomena. In contrast, volcano seismology involves subsurface sources, which are usually impossible to observe directly.

Due to the large length scales involved with volcanic eruptions, the majority of volcano acoustic oscillations occur at infrasonic frequencies. The relatively low acoustic attenuation in the atmosphere at these frequencies allows infrasound from large eruptions to propagate long distances and to be recorded globally. Recent studies have demonstrated how infrasound can be used to detect, locate, characterize, and quantify volcanic eruptions, as well as constrain various eruption source parameters. These studies have shown clear progress in hazard mitigation, and knowledge on volcano-infrasound source processes is expanding. In addition, volcanic signals have been used to study the propagation of sound and atmospheric structure.

Numerous sources of infrasound exist, and may be recorded both locally and globally. Examples of man-made infrasonic sources include explosions (Ceranna et al., 2009), high-speed aircraft (Liszka and Waldemark, 1995), rockets (Balachandran and Donn, 1971), and industrial activity (Liszka, 1974). Natural sources of infrasound are diverse: aurora (Wilson, 1967), lightning and sprites (Farges and Blanc, 2010), surf (Garces et al., 2006), wave–wave ocean interactions (microbaroms) (Waxler and Gilbert, 2006), avalanches (Scott et al., 2007), meteors (ReVelle, 1975), mountain-associated waves (Wilson et al., 2010) earthquakes (Mutschlecner and Whitaker, 2005), tsunamis (Le Pichon et al., 2005b), and of course volcanoes. The reader is referred to Le Pichon et al. (2010) for in-depth discussions of global infrasound research and monitoring.

The diverse nature of volcanic activity produces a wide variety of infrasound signals, and nearly all types of active volcanism have been documented to produce infrasound. In this manuscript we describe the various types of volcano infrasound signals and the physical processes inferred to produce them. We define local infrasound recordings as those within ~15 km of the volcano, regional from ~15 to 250 km distances, and global for >250 km distances. Here we emphasize regional and global volcano infrasound observations and modeling, and document the recent progress in this area. The dynamic atmosphere affects the propagation of infrasound at all observation ranges. Generally, however, as propagation range increases, the spatiotemporal variability of the atmosphere becomes increasingly significant, such that accurate characterization of the atmosphere from 0 to 140 km altitude is necessary to interpret long-range infrasound recordings. This manuscript is not intended to be a comprehensive review of the volcano infrasound literature; the reader is referred to Johnson and Ripepe (2011), and Garces et al. (in press) for more references and information on the subject and Arrowsmith et al. (2010) for a review on seismoacoustics. A primer on infrasound and acoustics is given in Section 2, followed by a description of the history of volcano infrasound in Section 3. Section 4 describes typical signals and models for various types of volcanic activity, while Section 5 focuses on regional and global observations and propagation modeling of volcano infrasound. We conclude with a discussion of future directions in the field (Section 6).

2. Infrasound and acoustics primer

Acoustic energy is produced by a multitude of oscillatory processes. Once generated, acoustic energy propagates as a mechanical pressure wave through a medium. In the atmosphere, sound waves propagate within a gas, compressing and rarifying the medium. Acoustic energy in the atmosphere propagates as a compressional or longitudinal wave as its motion is in the same direction as its propagation. No shear waves are supported. Sound is also produced over a wide range of frequencies: audible between ~20–20,000 Hz, ultrasound above 20,000 Hz, and infrasound below 20 Hz. At even lower frequencies (and longer wavelengths) gravity begins to act as a restoring force on the pressure wave, creating acoustic-gravity waves (Pierce, 1981).

The speed of sound c, in an ideal gas is given by:

$$c = \sqrt{\gamma R T} \tag{1}$$

where γ is the specific heat ratio, R is the universal gas constant, and T is the temperature (Pierce, 1981). The sound speed is thus proportional to the square root of the temperature, and is 343 m/s in a typical 20 °C atmosphere at sea level. Extremely high amplitude sources can produce supersonic waves that propagate faster than the speed of sound and produce nonlinear shock waves, which decay and eventually transition to linear sound waves. In addition to temperature (Eq. (1)), wind also affects the propagation path and travel times, and will be discussed along with long-range sound propagation in Section 5.

Acoustic energy loss in the atmosphere (attenuation) results from two main processes: absorption and geometrical spreading. Absorption in the atmosphere is further divided into two types: classical and rotational. Classical losses are associated with the transfer of energy from the kinetic energy of the gas molecules to heat, while rotational losses are associated with excitation of the gas molecules' energy states. Absorption of acoustic energy varies in the atmosphere with height, and at low frequencies decreases with frequency approximately to the power of 2. The relatively low amount of absorption in the infrasound band (~10^{-6} dB/km at 0.1 Hz vs. ~2.4 dB/km at 125 Hz) (Sutherland and Bass, 2004) allows infrasound to propagate long distances (up to thousands of kilometers). Geometric spreading occurs as a consequence of wavefront expansion. For a point source in an unbounded homogeneous medium, spherical spreading prevails and the pressure decreases as $1/r$, where r is the distance. Cylindrical spreading can result from either an extended (line) source or where the normally spherically spreading wave propagates in a waveguide (duct) (Section 5). The pressure loss for cylindrical spreading occurs as $1/\sqrt{r}$ (Pierce, 1981).

Energy in the wave is conserved as it spreads but not as it is absorbed. Energy losses due to ground reflections are typically negligible at infrasonic frequencies; consequently, little energy is lost to ground-bounces in long-range ducting. Scattering of acoustic energy from turbulence in the atmosphere and diffraction from and around topography are additional sources of attenuation (Salomons, 2001). Volcanic topography is often pronounced, resulting in amplitude losses and waveform distortion, which require accounting for at local (<15 km) propagation ranges (Matoza et al., 2009b).

Two other relevant concepts are that of the compact source and far-field. An acoustic source can be considered compact when its largest dimension, l, is much smaller than the radiated sound wavelength: $kl << 1$, where $k = 2\pi/\lambda$ is the wavenumber. This relationship is usually met in volcanic environments, unless the source is extremely large. Plane-wave propagation occurs when an acoustic wave is in the far-field. This assumes the acoustic field quantities change with time and with one spatial dimension, but do not change with position normal