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Volcano Infrasound: Progress and Future Directions

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PERSPECTIVES

Volcano infrasound: progress and future directions

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Abstract
Over the past two decades (2000–2020), volcano infrasound (acoustic waves with frequencies less than 20 Hz propagating in the atmosphere) has evolved from an area of academic research to a useful monitoring tool. As a result, infrasound is routinely used by volcano observatories around the world to detect, locate, and characterize volcanic activity. It is particularly useful in confirming subaerial activity and monitoring remote eruptions, and it has shown promise in forecasting paroxysmal activity at open-vent systems. Fundamental research on volcano infrasound is providing substantial new insights on eruption dynamics and volcanic processes and will continue to do so over the next decade. The increased availability of infrasound sensors will expand observations of varied eruption styles, and the associated increase in data volume will make machine learning workflows more feasible. More sophisticated modeling will be applied to examine infrasound source and propagation effects from local to global distances, leading to improved infrasound-derived estimates of eruption properties. Future work will use infrasound to detect, locate, and characterize moving flows, such as pyroclastic density currents, lahars, rockfalls, lava flows, and avalanches. Infrasound observations will be further integrated with other data streams, such as seismic, ground- and satellite-based thermal and visual imagery, geodetic, lightning, and gas data. The volcano infrasound community should continue efforts to make data and codes accessible and to improve diversity, equity, and inclusion in the field. In summary, the next decade of volcano infrasound research will continue to advance our understanding of complex volcano processes through increased data availability, sensor technologies, enhanced modeling capabilities, and novel data analysis methods that will improve hazard detection and mitigation.

Keywords Volcano infrasound · Acoustics · Volcano monitoring · Machine learning · Source and propagation modeling · Diversity · Equity · Inclusion

Introduction

Volcanic activity frequently generates low-frequency (< 20 Hz) acoustic waves in the atmosphere, known as infrasound. Analysis of volcano infrasound signals is increasingly common in both research and monitoring applications, leading to an ever-growing body of literature. Several review

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This paper constitutes part of a topical collection:

Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

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articles over the last two decades (2000–2020) have emphasized various aspects of the field: Harris and Ripepe (2007) considered historic infrasound studies and illustrated how infrasound can be combined with seismic and thermal data; Fee and Matoza (2013) discussed the range of infrasound signals from different eruption styles and provided an overview of the development of volcano infrasound; Johnson (2019) reviewed the use of infrasound in local eruption monitoring; and De Angelis et al. (2019) focused on the use of linear acoustic theory to estimate eruption source parameters. Work on infrasound-based remote eruption detection and early warning systems is reviewed by Matoza et al. (2019), Ripepe and Marchetti (2019), Taisne et al. (2019), and others in the book by Le Pichon et al. (2019). Here, we highlight promising advances over the past two decades and speculate on directions during the coming decade for the field as a whole, including eruption monitoring, source and propagation physics, instrumentation, and accessibility to broader research and monitoring communities.

Eruption monitoring

Over the past two decades (2000–2020), infrasound has transitioned from an exploratory research topic to an established, valuable, real-time monitoring tool employed by volcano observatories worldwide. Numerous studies have shown how infrasound can provide a continuous, detailed record of explosive and effusive activity (e.g., Ripepe et al. 2002; Vergniolle & Ripepe 2008; Matoza et al. 2019; Johnson 2019). Infrasound data complement seismic data by providing unambiguous evidence of surficial or shallow subsurface activity. Unlike ground- or satellite-based optical sensing, infrasound recording is not impacted by poor visibility, and data latency for local installations is usually less than a few tens of seconds. In its most basic application, infrasound can be used to detect and locate explosions (e.g., Matoza et al. 2011, 2017; De Angelis et al. 2012), while more advanced data processing can characterize diverse eruptive activity (Anderson et al. 2018a), discriminate between closely spaced vents (Ripepe et al. 2007; Fee et al. 2021), help forecast eruptions (Garcés et al. 1999; Ulivieri et al. 2013; Johnson et al. 2018; Ripepe et al. 2018), and provide quantitative eruption source parameters (e.g., Vergniolle & Caplan-Auerbach 2006; Ripepe et al. 2013; Fee et al. 2017). Near-real-time eruption monitoring with infrasound has been useful at well-monitored volcanoes, including at Tungurahua (Fee et al. 2010), Etna (Ripepe et al. 2018), Stromboli (Le Pichon et al. 2021), Kilauea (Patrick et al. 2019), and Sakurajima (Yokoo et al. 2013). Additionally, infrasound is used extensively by volcano observatories as it permits monitoring of remote regions and inaccessible areas (e.g., Cannata et al. 2013; Nishida & Ichihara 2016; Coombs et al. 2019; Diaz-Moreno et al. 2020).

Anticipated advances in eruption monitoring using infrasound will go beyond simple detection and source localization by providing detailed insight into eruption dynamics. Estimates of eruption mass and mass flow rate using infrasound appear possible (Fee et al. 2017), and will likely become a reality in the next decade, potentially in near-real-time for large eruptions. Open-vent volcanoes present a compelling opportunity for eruption forecasting using infrasound, and the theoretical groundwork has been laid to track changes in lava lake level (e.g., Johnson et al. 2018; Watson et al. 2019, 2020; Ishii & Yokoo 2021) and degassing intensity (e.g., Ripepe et al. 2002, 2010a; Petersen & McNutt 2007). Future work will implement these tools in near-real-time.

Volcanic sources

Infrasound can be used to quantify eruption parameters including volumetric and mass flow rates (e.g., Harris et al. 2013; Kim et al. 2015; Fee et al. 2017), directionality of eruptive blasts (e.g., Kim et al. 2012; Jolly et al. 2017; Iezzi et al. 2019a), and plume height (e.g., Lamb et al. 2015; Caplan-Auerbach et al. 2010; Ripepe et al. 2013; Perttu et al. 2020a). Common approximations for volcanic sources are equivalent monopole, dipole, or quadrupole sources following the canonical work of Woulff & McGetchin (1976), which was based on the acoustic analogy theory of Lighthill (1952). These source models have been useful in interpreting infrasound observations (e.g., Moran et al. 2008; Caplan-Auerbach et al. 2010; Johnson & Miller 2014; Fee et al. 2017; Yamada et al. 2017); however, they are not always applicable for the complex dynamics that occur during a volcanic eruption (cf. Matoza et al. 2009a, 2013). Numerical simulations (Taddeucci et al. 2014; Cerminara et al. 2016; Brogi et al. 2018; Watson et al. 2021a) and laboratory studies (Swanson et al. 2018; Peña Fernández et al. 2020) have examined volcanic jets, which are complex, directional sources, and provide a first step towards more realistic source models. Significant advances are likely to come from adapting and integrating results from modern aeroacoustic and jet noise studies into the volcano infrasound community (Matoza et al. 2009a), as well as from combining simulation and laboratory results with field observations to investigate infrasound source processes and quantify uncertainties.

Several studies have used infrasound signals to detect and locate surficial mass movements (a recent review is provided by Allstadt et al. 2018) such as pyroclastic density currents (Ripepe et al. 2010b; Delle Donne et al. 2014; Yamasato 1997), rockfalls (Moran et al. 2008; Johnson & Ronan 2015), lahars (Johnson & Palma 2015; Bosa et al. 2021), snow and rock avalanches (Marchetti et al. 2015; Toney et al. 2021; Watson et al. 2021b), debris flows (Marchetti et al. 2019), and lava flows (Garcés et al. 2003). These hazardous flows are spatially distributed, moving sources that can travel many kilometers and at fast speeds (> 10 m/s), with lahars, rockfalls, avalanches, and debris flows having the potential to spontaneously occur without an associated volcanic eruption. Further study is needed to accurately model the infrasound generation from surficial mass movements (cf. Coco et al. 2021; Johnson et al. 2021) so that infrasound observations can be reliably used to quantitatively constrain flow properties and improve hazard mitigation efforts. In tandem, methods to detect potentially weak signals of surficial mass movements within realistic persistent and variable background noise must continue to be developed to achieve robust monitoring capabilities (Sanderson et al. 2021).

Infrasound propagation

Extensive work over the past decade has demonstrated the significance of wavefield interactions with topography such as scattering and diffraction (Matoza et al. 2009b; Kim & Lees 2011, 2014; Lacanna & Ripepe 2013; Kim et al. 2015; Ishii et al. 2020; Maher et al. 2021). The availability of low-cost unmanned aerial vehicles and affordable structure-from-motion software has allowed more researchers to create high-resolution digital elevation models (DEMs) of volcanic edifices, which can be used for modeling infrasound propagation. Incorporating topography can result in improved source localizations (Fig. 1; Fee et al. 2021), and improved estimations of volumetric and mass flow rates (Kim et al. 2015; Fee et al. 2017).

Infrasound is typically assumed to propagate linearly. Volcanic eruptions, however, are violent phenomena and acoustic waves are likely to behave nonlinearly near the source (Morrissey & Chouet 1997; Yokoo & Ishihara 2007; Marchetti et al. 2013). Several recent studies have

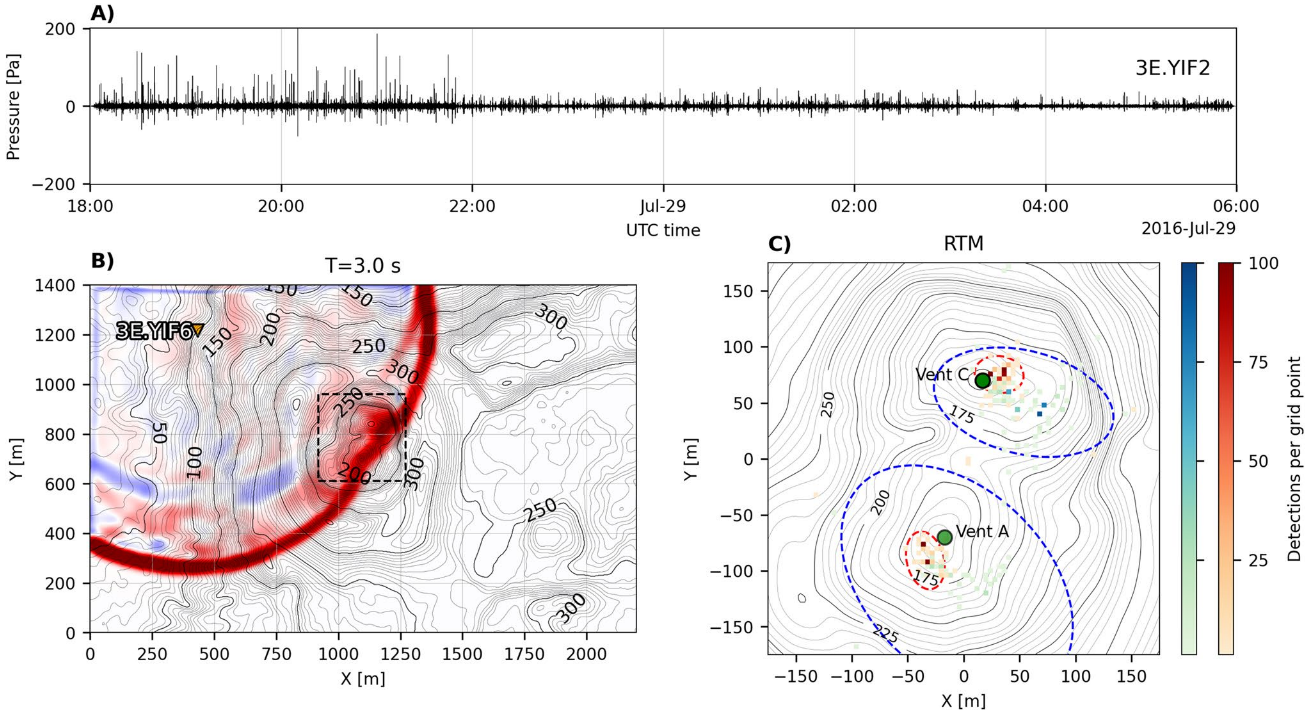

Fig. 1 Demonstration of the substantial effect of topography on the infrasonic wavefield and infrasound-derived locations at Yasur volcano, Vanuatu. **A** Twelve hours of infrasound data from a station deployed on the crater rim. Multiple explosions occur every minute. **B** Finite-difference time domain (FDTD) simulation snapshot at 3.0 s from Yasur station YIF6 propagating out across the study region. Red indicates a positive pressure (compression) while blue indicates a negative pressure (rarefaction) of the propagating acoustic wave at the ground surface. Dashed box shows extent of area in **C**. **C** 2-D histograms of 12 h of backprojected infrasound locations with travel times calculated using simple slant distances (blue colors) versus FDTD modeling (red colors). The two active vents are indicated by green circles, and the dashed ellipses represent 98.9% confidence regions. The FDTD approach detects more events and locates them closer to both vents in clear clusters, including over 400 events located at a single grid point near either vent. Elevation contour units are meters. Modified from Fee et al. (2021)

demonstrated that neglecting nonlinear effects may result in inaccurate infrasound-derived estimates of eruption properties (Anderson 2018; Brogi et al. 2018; Dragoni and Santoro 2020; Maher et al. 2020; Watson et al. 2021a). For example, aeroacoustic simulations by Watson et al. (2021a) show that changes to waveform shape due to nonlinear effects can lead to underestimation of total erupted volume (Fig. 2). Combining results from modeling studies with field observations and laboratory experiments will help to better understand nonlinear effects, when they should be accounted for, and how to integrate nonlinear effects into routine data analysis and monitoring efforts.

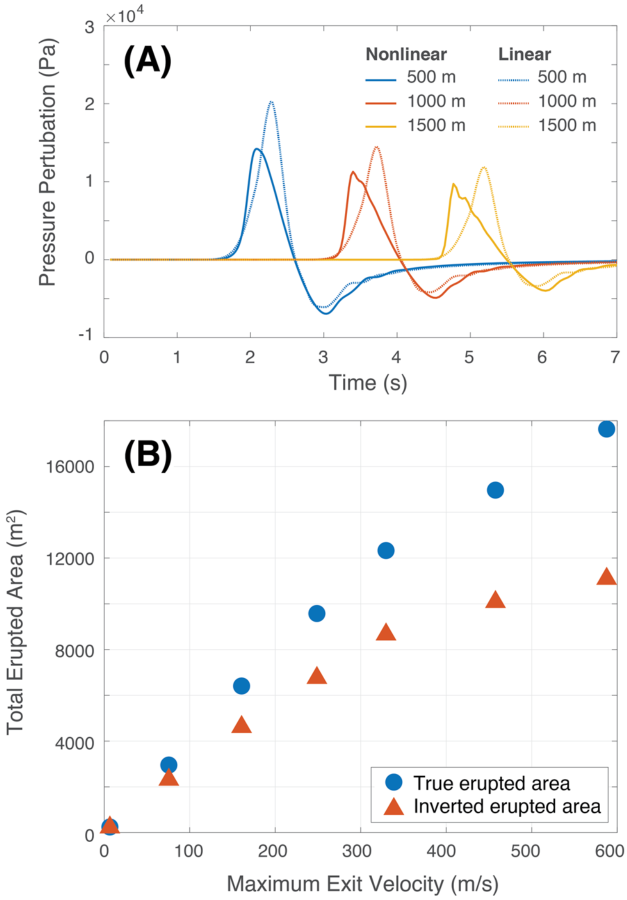

Fig. 2 **A** Comparison of synthetic infrasound signals from 2-D nonlinear aeroacoustic simulations (solid lines) and predictions based on linear monopole source model (dashed lines) at three different recording distances (blue, 500 m; red, 1000 m; yellow, 1500 m) for a maximum exit velocity of 588 m/s. Compared to waveforms predicted by the linear monopole source model, the nonlinear simulations feature steeper onsets and longer decay times. **B** Comparison of true erupted area in nonlinear aeroacoustic simulations (circles) with estimates from inversion of synthetic waveforms using linear monopole model (triangles) as a function of maximum exit velocity. Nonlinear waveform changes increase with exit velocity, leading to underestimation of erupted area when using linear acoustics model. Modified from Watson et al. (2021a)

Infrasound propagation depends upon meteorological conditions, with wind and temperature able to strongly influence infrasound observations, even at local distances (Fee & Garcés, 2007; Matoza et al. 2009b; Johnson et al. 2012; Lacanna et al. 2014). While some local infrasound studies have incorporated wind data into their analysis (Dabrowa et al. 2014; Ortiz et al. 2018), there remains a need to obtain more wind data at high temporal and spatial resolutions, and to incorporate meteorological expertise within the volcano infrasound community. At regional to global distances, atmospheric specifications from numerical weather prediction models for the lower atmosphere can be seamlessly combined with empirical models for the upper atmosphere using ground to space models (Drob et al. 2003; Schwaiger et al. 2019) to be used by propagation modeling methods such as ray tracing (Blom 2014) and the parabolic (Waxler et al. 2015) and Navier–Stokes equations (De Groot-Hedlin 2017). However, discrepancies between atmospheric propagation modeling and infrasound observations are often found when applying such approaches (Matoza et al. 2011; Green et al. 2012, 2018; Schwaiger et al. 2020; Iezzi et al. 2019b; Toney et al. 2021). Thus, we identify a need for future work on atmospheric model uncertainty and for inclusion of small-scale variability from sources such as gravity waves and topography in future long-range propagation modeling efforts. We note that this is also a current topic of research in other fields such as atmospheric physics and explosion monitoring (Le Pichon et al. 2019).

Instrumentation and computation

Infrasound microphones and associated equipment (digitizers and power supplies) are becoming smaller and lower in cost (e.g., Marcillo et al. 2012; Anderson et al. 2018b; Lamb et al. 2021) and, as a result, more widely used. The continued proliferation of infrasound sensors will result in more observations of varied styles of volcanic activity, which will help to validate existing hypotheses and pose new questions. Smaller, lower cost, and higher quality infrasound sensors, digitizers, and power supplies are allowing for novel deployments that will better and more completely characterize the acoustic wavefield. Large-*N* nodal infrasound surveys will be able to capture small-scale variations in the acoustic wavefield, while airborne sensors (Jolly et al. 2017; Iezzi et al. 2019a) will record vertical wavefield variations, which will better constrain the potential directionality of sources and quantify estimates of acoustic power. Recommendations for deployment topologies that were recently advanced by the volcano acoustics community (CONVERSE 2019) include the following: (1) more large-*N* style local deployments for research purposes, (2) inclusion of at least one infrasound sensor or array (but hopefully more) in local monitoring networks (McKee et al. 2018; Iezzi et al. 2020), and (3) a more dense global infrasound network to augment the International Monitoring System (Matoza et al. 2017, 2018), either through more arrays or by adding infrasound sensors to the existing seismic network (Wilson et al. 2018; Sanderson et al. 2020).

The increased number of sensors and data collection opportunities will facilitate improvements in machine learning (ML) methodologies, now common in volcano seismology (e.g., Malfante et al. 2018; Anzieta et al. 2019; Hajian et al. 2019), to complement existing data processing workflows. Unsupervised ML has already shown promise in distinguishing volcanic signals from noise (Fig. 3; Ortiz et al. 2020) and tracking changes in volcanic activity (Witsil & Johnson 2020; Watson 2020). However, to classify signals into predetermined categories, supervised ML is necessary. Supervised learning has been successful at locating infrasound sources at Mt. Etna, Italy (Cannata et al., 2011) and identifying various signals including mining blasts, earthquakes, and regional volcanic events (Albert & Linville 2020), but research is limited by a lack of labeled data to train ML models. Though raw data are readily available, labeling is time intensive and recorded signals are specific to the source processes, terrain, source-receiver distance, and atmosphere at specific volcanic centers. Looking forward, researchers should leverage strategies to increase the small amount of training data typically available. For example, adding domain specific data to generalized training data (i.e., transfer learning) has helped detect moonquakes (Civilini et al. 2021) and classify volcano seismic events (Titos et al. 2020). Integrated seismo-acoustic ML analysis will be particularly beneficial. Additionally, the volcano infrasound community is well positioned to synthetically create data given the various source time function models (Kinney & Graham 1985; Kim et al. 2021), atmospheric models (Schwaiger et al., 2019), and propagation software

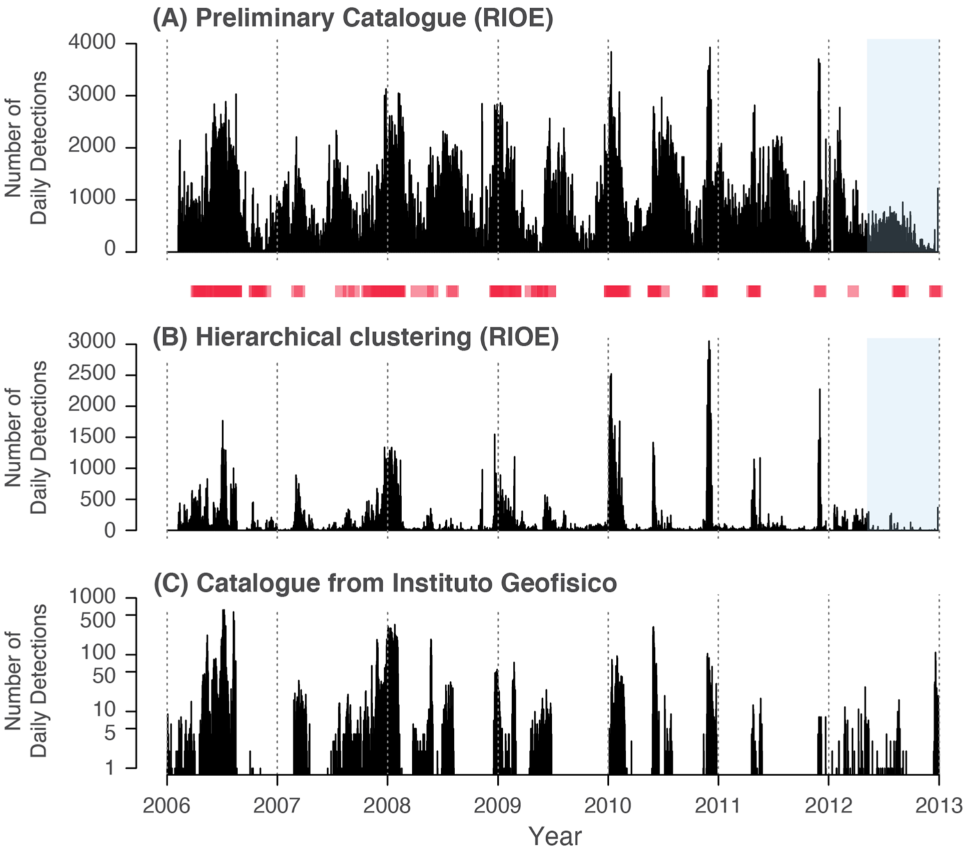

Fig. 3 Unsupervised machine learning applied to infrasound data from RIOE array, which is 37 km from Tungurahua. **A** Preliminary catalog showing the number of daily detections of signals originating within ± 10° of the expected back-azimuth (33°) to Tungurahua. **B** Daily count of impulsive signals found after applying hierarchical clustering to the preliminary catalog. **C** Daily analyst detections of impulsive signals using the local monitoring network run by the Instituto Geofisico. There is good agreement between the hierarchical clustering results (**B**) and the analyst catalog (**C**), with hierarchical clustering identifying more events. The red squares represent satellite detections of eruptive activity (color intensity scales with number of satellite detections), which are also well correlated with the hierarchical clustering results. Blue shaded areas in **A** and **B** indicate when only three out of the four microphones at RIOE were operational. Modified from Ortiz et al. (2020)

(Waxler et al. 2017) currently available. Along with other physics-based data augmentation strategies, this may supplant the need to collect and label large datasets and will help generalize ML methodologies. Along with ML techniques, advances in computing power including high performance computing and cloud-based processing (MacCarthy et al. 2020) will enable large-scale data processing, as well as facilitate more complex source modeling and propagation simulations at local and global scales.

To optimize efforts and make the most of existing data and analysis codes, and avoid reproducibility barriers affecting the sciences (Baker 2016), we encourage sharing data and codes with FAIR (Findable, Accessible, Interoperable, and Reusable) principles in mind. Recognizing this, many geoscience journals now require data archiving in long-term public repositories (cf. Stall et al. 2019). Geophysical data management centers permit easy access and re-use by others and are excellent places to archive data. In addition to open data, use of standard, open-source tools facilitates the reproduction of computational analyses. The growing acceptance of open-source standards and practices (e.g., Python, ObsPy (Beyreuther et al. 2010), and hosting code on public services such as GitHub) is a promising sign for our community. Well-documented and benchmarked open-source codes following good software development practices (Wilson et al. 2017) should continue to be developed and published, with coordination between research groups and funding agencies to avoid duplicated effort.

Integration with other data streams

Advances in instrumentation, analytical methods, and numerical and physics-based modeling permit adequate recording and integration of many observations of volcano phenomena that occur during magma storage, its migration to the surface, and subsequent eruption. Given their comparable sub-second time resolution, parameters allowing direct temporal comparison with infrasound now include seismicity, SO_2 gas flux, deformation (tilt, GNSS), thermal and visible cameras, and lightning (cf. Ripepe et al. 2002; Iguchi et al. 2008; Johnson and Miller 2014; Yamada et al. 2019; Smith et al. 2020; McKee et al. 2021a).

Volcano infrasound and seismology share similar physics and can be analyzed with similar processing techniques (e.g., Haney 2009; McNutt et al. 2015; Thelen et al., this issue). The combination of seismic and infrasound records can be used for robust detection (De Angelis et al. 2012; Ichihara et al. 2012) and back azimuth estimation of infrasonic sources (McKee et al. 2018). Differential arrival times between infrasound, seismic, and thermal signals have been used to infer explosive source depths (e.g., Sahetapy-Engel et al. 2008; Petersen & McNutt 2007; Richardson et al. 2014) and to examine source processes (e.g., Ripepe et al. 2001, 2002; Marchetti et al. 2009). Seismo-acoustic observations have been combined with tiltmeters and cameras to link internal and external volcanic processes such as deformation prior to explosions (e.g., Yokoo et al. 2009; Genco and Ripepe 2010; Lyons et al. 2012; Waite et al. 2013; Johnson et al. 2014), gradual pressurization of magmatic plumbing systems preceding eruptions (Cannata et al. 2015), and caldera collapse and lava effusion rates (Patrick et al. 2019).

Robust estimation of volume flow rate (VFR, in m^3/s, which is a proxy of mass eruption rate) from infrasound records remains a primary research target. The regular integration of DEMs in numerical modeling (Kim et al. 2015) now provides more accurate VFR estimates for short duration explosions that have been validated with independent SO_2, tephra, and thermal measurements (Dalton et al. 2010; Delle Donne et al. 2016; Fee et al. 2017). Estimating VFR for volcanic jet flows will require observing gas- to ash-rich flows with jet diameter length scales of meters (e.g., fumaroles, geysers) (Johnson et al. 2013; McKee et al. 2017) to hundreds of meters (i.e., VEI 4 + eruptions) (e.g., Matoza et al. 2009a, b; Fee et al. 2010; McKee et al. 2021a,b) with acoustic observations that extend vertically using airborne sensors (e.g., Jolly et al. 2017; Iezzi et al. 2019a; Brissaud et al. 2021), up-to-date DEMs, and high-speed thermal and visual data (e.g., Taddeucci et al. 2012; 2014; Gaudin et al. 2016). Field observations should be combined with analogue experiments (e.g., Medici et al. 2014; Cigala et al. 2017; Peña Fernández et al. 2020; Schmid et al. 2020), numerical modeling (e.g. Ogden et al. 2008; Cerminara et al. 2016; Watson et al. 2021a), and new data types such as continual radio frequency, which Méndez-Harper et al. (2018) recently suggested is caused by shock structures in volcanic jet flows.

The community still has much to uncover with multiparametric studies. The June 2019 eruption of Ulawun volcano, Papua New Guinea highlights the power of combining infrasound with other observations (Fig. 4; McKee et al. 2021b). The infrasound and SO_2 detections suggested jetting occurred for hours prior to satellite-based ash detection and that the eruption started more than 24 h before the main sequence with vigorous gas jetting (McKee et al. 2021b). Infrasonic observations of a long eruption sequence allow for connections to data streams yet to be explored, such as petrology-based crystal clocks (e.g. Landi et al. 2011; Lynn et al. 2018; Costa et al. 2020). Multidisciplinary approaches that combine infrasound; local and satellite thermal, ultraviolet, and visible imagery; seismic; lightning; and geological observations combined with modeling will continue to inform on eruptive processes and dynamics (e.g., Gurioli et al. 2008; Steffke et al. 2010; Perttu et al. 2020b; McKee et al. 2021a,b).

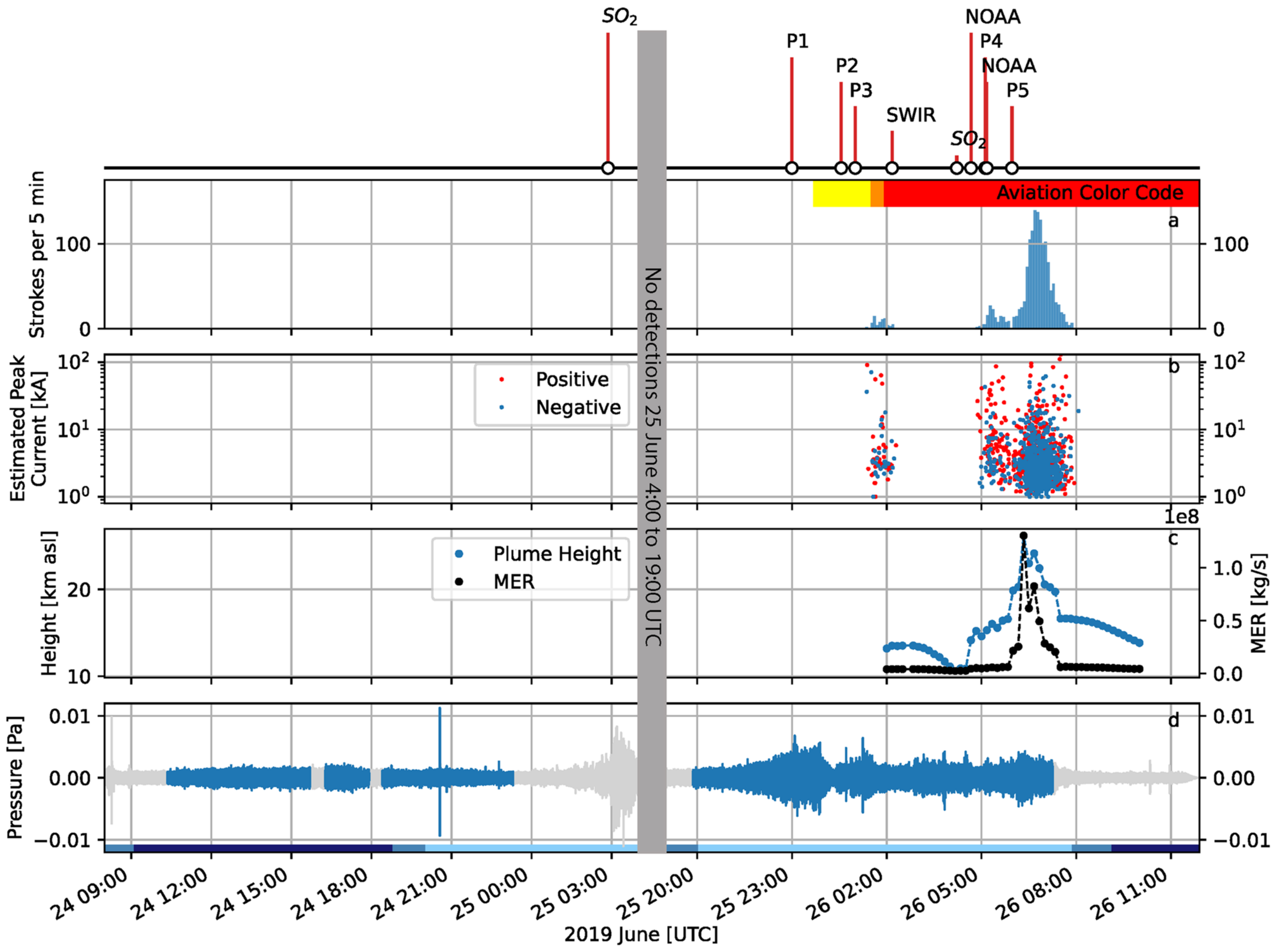

Fig. 4 Ulawun eruption sequence observations comparing discrete (red lines at top; SO2, pilot photos, NOAA ash plume detections, and shortwave infrared satellite (SWIR) observations) and time series (lightning, plume height, mass eruption rate (MER), infrasound) observations. **A** Lightning strokes per 5 min, **B** estimated peak current per stroke (red is positive; black is negative), **C** plume height (10 min increment) in blue and MER in black estimated from plume height, **D** beamformed infrasound trace with times of coherent detections plotted in blue. Infrasound data are filtered from 0.1 to 5 Hz. Modified from McKee et al. (2021b)

Diversity, equity, and inclusion

Our vision for the future of volcano infrasound is one in which the research community and collaborative infrastructure better incorporate the principles of diversity, equity, and inclusion (DEI). To narrow documented gaps in representation (Bernard and Cooperdock 2018; Dutt 2020), we need to align research and educational standard practices in our field with, for example, DEI strategic plans of the American Geophysical Union (AGU 2020) and the European Geophysical Union (EGU 2020), and to follow evidence-based practices for achieving DEI goals. For more details about discrimination in volcanology and recommendations to advance DEI in the volcanological community, see Kavanagh et al. (this issue).

Fundamental efforts towards advancing DEI should include better recruitment and retention of students and scientists from underrepresented demographic and geographic backgrounds at all career levels. Possible actions include providing expanded opportunities for marginalized students to attend workshops, conferences, and internships as well as training in networking and the development of improved mentoring relationships. There is a strong need to improve safety, accessibility, and inclusivity, particularly in field work but also in laboratory and classroom settings (Giles et al. 2020; Cooperdock et al. 2021). Ali et al. (2021) detail a practical roadmap of actions that organizations can take to address racism in the geosciences.

Equal access to resources and the development of low-cost instrumentation can be a foundation for mutually beneficial international collaboration and training of new scientists (Minasny et al. 2020). We recognize a vital need to include scientists and practitioners from nations where volcano hazards may be impactful but where monitoring infrastructure and training is underdeveloped. The inclusion of geographically diverse observatories in the advancement of infrasound science is beneficial both to the local institutions and to international partners. These partners must be respectful of operational needs of an observatory during crises and inclusive to ensure the collected data is analyzed collaboratively (CONVERSE 2019; IAVCEI 2015).

We emphasize that these listed points are merely a starting point that may improve the diversity, equity, and inclusivity in the field of volcano infrasound. We intend that DEI improvements will be a topic of ongoing discussion, evaluation, and change.

Conclusion

Infrasound is a useful tool for detecting, locating, and characterizing volcanic processes and monitoring volcanic activity at both local and global distances. Here we have summarized the progress made in volcano infrasound over the last two decades, and highlighted potential future research directions including: improved eruption monitoring, acoustic source characterization, infrasound propagation modeling, machine learning, and integration with other data streams. We envision that the future of the volcano infrasound community and collaborative research infrastructure will better incorporate the principles of DEI. The proliferation of infrasound stations, operated both by research groups and observatories, coupled with advances in computation, modeling, and analysis by a broad and diverse community will provide an increasing wealth of opportunities for improved eruption monitoring and research advances in the coming decade.

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References

AGU (2020) AGU's Ethics, Diversity, Equity and Inclusion 2020 Annual Report

Albert S, Linville L (2020) Benchmarking current and emerging approaches to infrasound signal classification. Seismol Res Lett 91(2):921–929. https://doi.org/10.1785/0220190116

Ali HN, Sheffield SL, Bauer JE, Caballero-Gill RP, Gasparini NM, Libarkin J, Gonzales KK, Willenbring J, Amir-Lin E, Cisneros J, Desai D, Erwin M, Gallant E, Jeannelle Gomez K, Keisling BA, Mahon R, Marin-Spiotta E, Welcome L, Schneider B (2021) An actionable anti-racism plan for geoscience organizations. Nat Commun 12:3794. https://doi.org/10.1038/s41467-021-23936-w

Allstadt KE, Matoza RS, Lockhart AB, Moran SC, Caplan-Auerbach J, Haney MM, Thelen WA, Malone SD (2018) Seismic and acoustic signatures of surficial mass movements at volcanoes. Journal of Volcanology and Geothermal Research. https://doi.org/10.1016/j.jvolgeores.2018.09.007

Anderson JF, Johnson JB, Steele AL, Ruiz MC, Brand BD (2018a) Diverse Eruptive Activity Revealed by Acoustic and Electromagnetic Observations of the 14 July 2013 Intense Vulcanian Eruption of Tungurahua Volcano, Ecuador. Geophys Res Lett 45(7):2976–2985. https://doi.org/10.1002/2017GL076419

Anderson JF, Johnson JB, Bowman DC, Ronan TJ (2018b) The Gem Infrasound Logger and Custom-Built Instrumentation. Seismol Res Lett 89(1):153–164. https://doi.org/10.1785/0220170067

Anderson JF (2018) Pressure waves and tephra dispersal from volcanic explosions: models, observations, and instrumentation. PhD thesis, Boise State University. https://doi.org/10.18122/td/1468/boisestate

Anzieta JC, Ortiz HD, Arias GL, Ruiz MC (2019) Finding Possible Precursors for the 2015 Cotopaxi Volcano Eruption Using Unsupervised Machine Learning Techniques. Int J Geophys. https://doi.org/10.1155/2019/6526898

Baker M (2016) 1,500 scientists lift the lid of reproducibility. Nature 533:452–454. https://doi.org/10.1038/533452A

Bernard RE, Cooperdock EH (2018) No progress on diversity in 40 years. Nat Geosci 11(5):292–295. https://doi.org/10.1038/s41561-018-0116-6

Beyreuther M, Barsch R, Krischer L, Megies T, Behr Y, Wassermann J (2010) ObsPy: A Python Toolbox for Seismology. Seismol Res Lett 81(3):530–533. https://doi.org/10.1785/gssrl.81.3.530

Blom PS (2014) GeoAc numerical tools to model acoustic propagation in the geometric limit. Los Alamos National Security

Bosa AR, Johnson JB, De Angelis S, Lyons JJ, Roca A, Anderson JF, Pineda A (2021) Tracking secondary lahar flow paths and characterizing pulses and surges using infrasound array networks at Volcán de Fuego, Guatemala. Volcanica 4(2):239–256. https://doi.org/10.30909/vol.04.02.239256

Brissaud Q, Krishnamoorthy S, Jackson JM, Bowman DC, Komjathy A, Cutts JA, Zhan Z, Pauken MT, Izraelevitz JS, Walsh GJ (2021) The first detection of an earthquake from a balloon using its acoustic signature. Geophysical Research Letters, 48(12). https://doi.org/10.1029/2021GL093013.

Brogi F, Ripepe M, Bonadonna C (2018) Lattice Boltzmann modeling to explain volcano acoustic source. Scientific Reports (May):1–8. https://doi.org/10.1038/s41598-018-27387-0

Cannata A, Montalto P, Aliotta M, Cassisi C, Pulvirenti A, Privitera E, Patanè D (2011) Clustering and classification of infrasonic events at Mount Etna using pattern recognition techniques. Geophys J Int 185(1):253–264. https://doi.org/10.1111/j.1365-246X.2011.04951.x

Cannata A, Di Grazia G, Aliotta M, Cassisi C, Montalto P, Patanè D (2013) Monitoring seismo-volcanic and infrasonic signals at volcanoes: Mt Etna case study. Pure Appl Geophys 170(11):1751–1771. https://doi.org/10.1007/s00024-012-0634-x

Cannata A, Spedalieri G, Behncke B, Cannavò F, Di Grazia G, Gambino S, Gresta S, Gurrieri S, Liuzzo M, Palano M (2015) Pressurization and depressurization phases inside the plumbing system of Mount Etna volcano: evidence from a multiparametric approach. J Geophys Res Solid Earth 120(9):5965–5982. https://doi.org/10.1002/2015JB012227

Caplan-Auerbach J, Bellesiles A, Fernandes JK (2010) Estimates of eruption velocity and plume height from infrasonic recordings of the 2006 eruption of Augustine Volcano, Alaska. J Volcanol Geoth Res 189(1–2):12–18. https://doi.org/10.1016/j.jvolgeores.2009.10.002

Cerminara M, Esposti Ongaro T, Neri A (2016) Large Eddy Simulation of gas-particle kinematic decoupling and turbulent entrainment in volcanic plumes. J Volcanol Geoth Res 326:143–171. https://doi.org/10.1016/j.jvolgeores.2016.06.018

Cigala V, Kueppers U, Peña Fernández JJ, Taddeucci J, Sesterhenn J, Dingwell DB (2017) The dynamics of volcanic jets: Temporal evolution of particles exit velocity from shock-tube experiments. J Geophys Res Solid Earth 122(8):6031–6045. https://doi.org/10.1002/2017JB014149

Civilini F, Weber RC, Jiang Z, Phillips D, Pan WD (2021) Detecting moonquakes using convolutional neural networks, a non-local training set, and transfer learning. Geophys J Int 225(3):2120–2134. https://doi.org/10.1093/gji/ggab083

Coco M, Marchetti E, Morandi O (2021) Numerical modeling of infrasound energy radiation by debris flow events. Pure Appl Geophys:1–13. https://doi.org/10.1007/s00024-021-02759-2

CONVERSE (2019) Community Network for Volcanic Eruption Response (CONVERSE) Infrasound Workshop Report. Fairbanks, Alaska

Coombs M, Wallace K, Cameron C, Lyons J, Wech A, Angeli K, Cervelli P (2019) Overview, chronology, and impacts of the 2016–2017 eruption of Bogoslof volcano, Alaska. Bull Volcanol 81:62. https://doi.org/10.1007/s00445-019-1322-9

Cooperdock EHG, Chen CY, Guevara VE, Metcalf JR (2021) Counteracting systemic bias in the lab, field, and classroom. AGU Advances 2(1):e2020AV000353. https://doi.org/10.1029/2020av000353

Costa F, Shea T, Ubide T (2020) Diffusion chronometry and the timescales of magmatic processes. Nat Rev Earth Environ 1(4):201–214. https://doi.org/10.1038/s43017-020-0038-x

Dabrowa AL, Green DN, Johnson JB, Phillips JC, Rust AC (2014) Comparing near-regional and local measurements of infrasound from Mount Erebus, Antarctica: implications for monitoring. J Volcanol Geoth Res 288:46–61. https://doi.org/10.1016/j.jvolgeores.2014.10.001

Dalton MP, Waite GP, Watson IM, Nadeau PA (2010) Multiparameter quantification of gas release during weak Strombolian eruptions at Pacaya volcano, Guatemala. Geophys Res Lett 37:L09303. https://doi.org/10.1029/2010GL042617

De Groot-Hedlin CD (2017) Infrasound propagation in tropospheric ducts and acoustic shadow zones. J Acoust Soc Am 142(4):1816–1827. https://doi.org/10.1121/1.5005889

De Angelis S, Diaz-Moreno A, Zuccarello L, De Angelis S, Diaz-Moreno A, Zuccarello L (2019) Recent developments and applications of acoustic infrasound to monitor volcanic emissions. Remote Sensing 11(11):1302. https://doi.org/10.3390/rs11111302

De Angelis S, Fee D, Haney M, Schneider D (2012) Detecting hidden volcanic explosions from Mt. Cleveland Volcano, Alaska with infrasound and ground coupled airwaves. Geophys Res Lett 39(21):1–6, DOI https://doi.org/10.1029/2012GL053635

Delle Donne D, Ripepe M, Angelis SD, Cole PD, Lacanna G, Poggi P, Stewart R (2014) Thermal, acoustic and seismic signals from pyroclastic density currents and Vulcanian explosions at Soufriere Hills Volcano, Montserrat. In: Wadge G, Robertson REA, Voight B (eds) The Eruption of Soufriere Hills Volcano, Montserrat from 2000 to 2010. Geological Society, London, pp 169–178

Delle Donne D, Ripepe M, Lacanna G, Tamburello G, Bitetto M, Aiuppa A (2016) Gas mass derived by infrasound and UV cameras: implications for mass flow rate. J Volcanol Geoth Res 325:169–178. https://doi.org/10.1016/j.jvolgeores.2016.06.015

Diaz-Moreno A, Roca A, Lamur A, Munkli BH, Ilanko T, Pering TD, Pineda A, De Angelis S (2020) Characterization of acoustic infrasound signals at Volcán de Fuego, Guatemala: a baseline for volcano monitoring. Front Earth Sci. https://doi.org/10.3389/feart.2020.549774

Dragoni M, Santoro D (2020) A model for the atmospheric shock wave produced by a strong volcanic explosion. Geophys J Int 222(2):735–742. https://doi.org/10.1093/gji/ggaa205

Drob DP, Picone JM, Garc es M (2003) Global morphology of infrasound propagation. Journal of Geophysical Research: Atmospheres 108(21):4680. https://doi.org/10.1029/2002jd003307

Dutt K (2020) Race and racism in the geosciences. https://doi.org/10.1038/s41561-019-0519-z

EGU (2020) Equality, Diversity, and Inclusion Working Group

Fee D, Izbekov P, Kim K, Yokoo A, Lopez T, Prata F, Kazahaya R, Nakamichi H, Iguchi M (2017) Eruption mass estimation using infrasound waveform inversion and ash and gas measurements: evaluation at Sakurajima Volcano, Japan. Earth Planet Sci Lett 480:42–52. https://doi.org/10.1016/J.EPSL.2017.09.043

Fee D, Toney L, Kim K, Sanderson RW, Iezzi AM, Matoza RS, De Angelis S, Jolly AD, Lyons JJ, Haney MM (2021) Local explosion detection and infrasound localization by reverse time migration using 3-D finite-difference wave propagation. Front Earth Sci 9:1. https://doi.org/10.3389/feart.2021.620813

Fee D, Garcés M (2007) Infrasonic tremor in the diffraction zone. Geophys Res Lett 34(16). https://doi.org/10.1029/2007GL030616

Fee D, Garces M, Steffke A (2010) Infrasound from Tungurahua volcano 2006-2008: Strombolian to Plinian activity. J Volcanol Geotherm Res 193(1-2):67–81. https://doi.org/10.1016/j.jvolgeores.2010.03.006

Fee D, Matoza RS (2013) An overview of volcano infrasound: from Hawaiian to plinian, local to global. J Volcanol Geotherm Res:123–137. https://doi.org/10.1016/j.jvolgeores.2012.09.002

Garcés M, Iguchi M, Ishihara K, Morrissey M, Sudo Y, Tsutsui T (1999) Infrasonic precursors to a Vulcanian eruption at Sakurajima Volcano, Japan. Geophys Res Lett 26(16):2537–2540

Garcés M, Harris A, Hetzer C, Johnson J, Rowland S, Marchetti E, Okubo P (2003) Infrasonic tremor observed at Kilauea volcano, Hawaii. Geophys Res Lett 30(20). https://doi.org/10.1029/2003GL018038.

Gaudin D, Taddeucci J, Houghton BF, Orr TR, Andronico D, Del Bello E, Kueppers U, Ricci T, Scarlato P (2016) 3-D high-speed imaging of volcanic bomb trajectory in basaltic explosive eruptions. Geochem Geophys Geosyst 17(10):4268–4275. https://doi.org/10.1002/2016GC006560

Genco R, Ripepe M (2010) Inflation-deflation cycles revealed by tilt and seismic records at Stromboli volcano. Geophys Res Lett 37(12). https://doi.org/10.1029/2010GL042925

Giles S, Jackson C, Stephen N (2020) Barriers to fieldwork in undergraduate geoscience degrees. Nat Rev Earth Environ 1(2):77–78. https://doi.org/10.1038/s43017-020-0022-5

Green DN, Matoza RS, Vergoz J, Le Pichon A (2012) Infrasonic propagation from the 2010 Eyjafjallajkull eruption: Investigating the influence of stratospheric solar tides. J Geophys Res Atmos 117(21):21202. https://doi.org/10.1029/2012JD017988

Green DN, Waxler R, Lalande JM, Velea D, Talmadge C (2018) Regional infrasound generated by the Humming Roadrunner ground truth experiment. Geophys J Int 214(3):1847–1864. https://doi.org/10.1093/GJI/GGY232

Gurioli L, Harris AJL, Houghton BF, Polacci M, Ripepe M (2008) Textral and geophysical characterization of explosive basaltic activity at Villarrica volcano. J Geophys Res Solid Earth 113:B8. https://doi.org/10.1029/2007JB005328

Hajian A, Cannavò F, Greco F, Nunnari G (2019) Classification of Mount Etna (Italy) volcanic activity by machine learning approaches. Ann Geophys 62:231. https://doi.org/10.4401/ag-8049

Haney MM (2009) Infrasonic ambient noise interferometry from correlations of microbaroms. Geophysical Research Letters, 36(19), DOI: https://doi.org/10.1029/2009GL040179.

Harris A, Ripepe M (2007) Synergy of multiple geophysical approaches to unravel explosive conduit and source dynamics - A case study from Stromboli. Geochemistry 67(1):1–35. https://doi.org/10.1016/j.chemer.2007.01.003

Harris AJL, Delle Donne D, Dehn J, Ripepe M, Worden AK (2013) Volcanic plume and bomb field masses from thermal infrared camera imagery. Earth Planet Sci Lett 365:77–85. https://doi.org/10.1016/j.epsl.2013.01.004

IAVCEI (2015) Guidelines on the roles and responsibilities of scientists involved in volcanic hazard evaluation, risk mitigation, and crisis response. https://www.iavceivolcano.org/iavcei/iavcei-guidelines-on-the-roles-and-responsibilities-of-scientists-involved-in-volcanic-hazard-evaluation-risk-mitigation-and-crisis-response/. Accessed 1 Feb 2022

Ichihara M, Takeo M, Yokoo A, Oikawa J, Ohminato T (2012) Monitoring volcanic activity using correlation patterns between infrasound and ground motion. Geophys Res Lett 39(4):1–5. https://doi.org/10.1029/2011GL050542

Iezzi AM, Schwaiger HF, Fee D, Haney MM (2019b) Application of an updated atmospheric model to explore volcano infrasound propagation and detection in Alaska. J Volcanol Geoth Res 371:192–205. https://doi.org/10.1016/j.jvolgeores.2018.03.009

Iezzi AM, Fee D, Haney MM, Lyons JJ (2020) Seismo-acoustic characterization of Mount Cleveland volcano explosions. Front Earth Sci 8:496. https://doi.org/10.3389/feart.2020.573368

Iezzi AM, Fee D, Kim K, Jolly AD, Matoza RS (2019a) Three-dimensional acoustic multipole waveform inversion at Yasur Volcano, Vanuatu. Journal of Geophysical Research: Solid Earth. https://doi.org/10.1029/2018JB017073

Iguchi M, Yakiwara H, Tameguri T, Hendrasto M, Hirabayashi JI (2008) Mechanism of explosive eruption revealed by geophysical observations at the Sakurajima, Suwanosejima and Semeru volcanoes. J Volcanol Geoth Res 178(1):1–9. https://doi.org/10.1016/j.jvolgeores.2007.10.010

Ishii K, Yokoo A (2021) Combined approach to estimate the depth of the magma surface in a shallow conduit at Aso volcano, Japan. Earth, Planets and Space 73(1):1–5. https://doi.org/10.1186/s40623-021-01523-z

Ishii K, Yokoo A, Iguchi M, Fujita E (2020) Utilizing the solution of sound diffraction by a thin screen to evaluate infrasound waves attenuated around volcano topography. J Volcanol Geoth Res 402:106983. https://doi.org/10.1016/j.jvolgeores.2020.106983

Johnson JB (2019) Local volcano infrasound monitoring. In: Infrasound Monitoring for Atmospheric Studies: Challenges in Middle Atmosphere Dynamics and Societal Benefits: Second Edition, Springer International Publishing, pp 989–1022. https://doi.org/10.1007/978-3-319-75140-5_32

Johnson JB, Miller AJC (2014) Application of the monopole source to quantify explosive flux during vulcanian explosions at Sakurajima Volcano (Japan). Seismol Res Lett 85(6):1163–1176. https://doi.org/10.1785/0220140058

Johnson JB, Ronan TJ (2015) Infrasound from volcanic rockfalls. J Geophys Res Solid Earth 120(12):8223–8239. https://doi.org/10.1002/2015JB012436

Johnson JB, Palma JL (2015) Lahar infrasound associated with Villarrica's March 3, 2015 eruption. Geophys Res Lett pp 6324-6331. https://doi.org/10.1002/2015GL065024

Johnson JB, Anderson J, Marcillo O, Arrowsmith S (2012) Probing local wind and temperature structure using infrasound from Volcan Villarrica (Chile). J Geophys Res 117. https://doi.org/10.1029/2012JD017694

Johnson JB, Anderson JF, Anthony RE, Sciotto M (2013) Detecting geyser activity with infrasound. Journal of volcanology and geothermal research, 256, 105–117. https://doi.org/10.1016/j.jvolgeores.2013.02.016

Johnson JB, Lyons JJ, Andrews BJ, Lees JM (2014) Explosive dome eruptions modulated by periodic gas-driven inflation. Geophys Res Lett 41. https://doi.org/10.1002/2014GL061310

Johnson JB, Watson LM, Palma JL, Dunham EM, Anderson JF (2018) Forecasting the eruption of an open-vent volcano using resonant infrasound tones. Geophys Res Lett. https://doi.org/10.1002/2017GL076506

Johnson JB, Anderson JF, Marshall HP, Havens S, Watson LM (2021) Snow avalanche detection and source constraints made using a networked array of infrasound sensors. J Geophys Res Earth Surf. https://doi.org/10.1029/2020JF005741

Jolly AD, Matoza RS, Fee D, Kennedy BM, Iezzi AM, Fitzgerald RH, Austin AC, Johnson R (2017) Capturing the acoustic radiation pattern of strombolian eruptions using infrasound sensors aboard a tethered aerostat, Yasur volcano, Vanuatu. Geophys Res Lett 44(19):9672–9680. https://doi.org/10.1002/2017GL074971

Kavanagh J, Annen CJ, Burchardt S, Chalk C, Gallant E, Morin J, Scarlett J, Williams R. (2022) Volcanologists - Who are we and where are we going? Bulletin of Volcanology.

Kim K, Lees JM (2014) Local volcano infrasound and source localization investigated by 3D simulation. Seismol Res Lett 85(6):1177–1186. https://doi.org/10.1785/0220140029

Kim K, Fee D, Yokoo A, Lees JM (2015) Acoustic source inversion to estimate volume flux from volcanic explosions. Geophys Res Lett 42(13):5243–5249. https://doi.org/10.1002/2015GL064466

Kim K, Lees JM (2011) Finite-difference time-domain modeling of transient infrasonic wavefields excited by volcanic explosions. Geophys Res Lett 38(L06804). https://doi.org/10.1029/2010GL046615

Kim K, Lees JM, Ruiz M (2012) Acoustic multipole source model for volcanic explosions and inversion for source parameters. Geophys J Int :1192–1204. https://doi.org/10.1111/j.1365-246X.2012.05696.x

Kim K, Rodgers AR, Garces MA, Myers SC (2021) Empirical acoustic source model for chemical explosions in air. Bulletin of the Seismological Society of America. https://doi.org/10.1785/0120210030

Kinney GF, Graham KJ (1985) Explosive Shocks in Air. Springer-Verlag. https://doi.org/10.1007/978-3-642-86682-1

Lacanna G, Ripepe M (2013) Influence of near-source volcano topography on the acoustic wave eld and implication for source modeling. J Volcanol Geoth Res 250:9–18. https://doi.org/10.1016/j.jvolgeores.2012.10.005

Lacanna G, Ichihara M, Iwakuni M, Takeo M, Iguchi M, Ripepe M (2014) Influence of atmospheric structure and topography on infrasonic wave propagation. J Geophys Res Solid Earth 119(4):2988–3005. https://doi.org/10.1002/2013JB010827

Lamb OD, De Angelis S, Lavallée Y (2015) Using infrasound to constrain ash plume rise. J Appl Volcanol 4(1):1–9. https://doi.org/10.1186/s13617-015-0038-6

Lamb OD, Shore MJ, Lees JM, Lee SJ, Hensman SM (2021) Assessing raspberry shake and boom sensors for recording African elephant acoustic vocalizations. Frontiers in Conservation Science. https://doi.org/10.3389/fcosc.2020.630967

Landi P, Marchetti E, La Felice S, Ripepe M, Rosi M (2011) Integration petrochemical and geophysical data reveals thermal distribution of the feeding conduits at Stromboli volcano, Italy. Geophysical Research Letters 38(8). https://doi.org/10.1029/2010GL046296

Le Pichon A, Pilger C, Ceranna L, Marchetti E, Lacanna G, Souty V, Vergoz J, Listowski C, Hernandez B, Mazet-Roux G, Duport A, Hereil P (2021) Using dense seismo-acoustic network to provide timely warning on the 2019 paroxsymal Stromboli eruptions. Sci Rep 11:14464. https://doi.org/10.1038/s41598-021-93942-x

Le Pichon A, Blanc E, Hauchecorne, A (Eds.) (2019) Infrasound monitoring for atmospheric studies: Challenges in middle atmosphere dynamics and societal benefits. Springer.

Lighthill MJ (1952) On sound generated aerodynamically: I. General theory. Proc Roy Soc London Ser A 211:564–587

Lynn KJ, Shea T, Garcia MO, Costa F, Norman MD (2018) Lithium diffusion in olivine records magmatic priming of explosive basaltic eruptions. Earth Planet Sci Lett 500:127–135. https://doi.org/10.1016/j.epsl.2018.08.002

Lyons JJ, Waite GP, Ichihara M, Lees JM (2012) Tilt prior to explosions and the effect of topography on ultra-long-period seismic records at Fuego volcano, Guatemala. Geophys Res Lett 39(8):8305. https://doi.org/10.1029/2012GL051184

MacCarthy J, Marcillo O, Trabant C (2020) Seismology in the cloud: a new streaming workflow. Seismol Res Lett 91(3):1804–1812. https://doi.org/10.1785/0220190357

Maher SP, Matoza RS, Groot-Hedlin CD, Gee KL, Fee D, Yokoo A (2020) Investigating spectral distortion of local volcano infrasound by nonlinear propagation at Sakurajima Volcano, Japan. J Geophys Res Solid Earth 125(3). https://doi.org/10.1029/2019JB018284

Maher SP, Matoza R, de Groot-Hedlin C, Kim K, Gee K (2021) Evaluating the applicability of a screen diffraction approximation to local volcano infrasound. Volcanica pp 67–85. https://doi.org/10.30909/vol.04.01.6785

Malfante M, Dalla Mura M, Metaxian JP, Mars JI, Macedo O, Inza A (2018) Machine learning for volcano-seismic signals: challenges and perspectives. IEEE Signal Process Mag 35(2):20–30. https://doi.org/10.1109/MSP.2017.2779166

Marchetti E, Ripepe M, Harris AJL, Delle Donne D (2009) Tracing the differences between Vulcanian and Strombolian explosions using infrasonic and thermal radiation energy. Earth Planet Sci Lett 279(3-4):273–281. https://doi.org/10.1016/j.epsl.2009.01.004

Marchetti E, Ripepe M, Delle Donne D, Genco R, Finizola A, Garaebiti E (2013) Blast waves from violent explosive activity at Yasur volcano, Vanuatu. Geophys Res Lett 40:5838–5843. https://doi.org/10.1002/2013GL057900

Marchetti E, Ripepe M, Ulivieri G, Kogelnig A (2015) Infrasound array criteria for automatic detection and front velocity estimation of snow avalanches: towards a real-time early warning system. Nat Hazards Earth Syst Sci 15:2545–2555. https://doi.org/10.5194/nhess-15-2545-2015

Marchetti E, Walter F, Barfucci G, Genco R, Wenner M, Ripepe M, McArdell B, Price C (2019) Infrasound array analysis of debris flow activity and implication for early warning. J Geophys Res Earth Surf 124:567–587. https://doi.org/10.1029/2018JF004785

Marcillo O, Johnson JB, Hart D (2012) Implementation, characterization, and evaluation of an inexpensive low-power low-noise infrasound sensor based on a micromachined differential pressure transducer and a mechanical filter. J Atmos Oceanic Tech 29(9):1275–1284. https://doi.org/10.1175/JTECH-D-11-00101.1

Matoza RS, Le Pichon A, Vergoz J, Herry P, Lalande JM, Hi L, Che IY, Rybin A (2011) Infrasonic observations of the June 2009 Sarychev Peak eruption, Kuril Islands: implications for infrasonic monitoring of remote explosive volcanism. J Volcanol Geoth Res 200(1–2):35–48. https://doi.org/10.1016/j.jvolgeores.2010.11.022

Matoza RS, Fee D, Neilsen TB, Gee KL, Ogden DE (2013) Aeroacoustics of volcanic jets: Acoustic power estimation and jet velocity dependence. J Geophys Res Solid Earth 118:6269–6284. https://doi.org/10.1002/2013JB010303

Matoza RS, Green DN, Le Pichon A, Shearer PM, Fee D, Mialle P, Ceranna L (2017) Automated detection and cataloging of global explosive volcanism using the International Monitoring System infrasound network. J Geophys Res Solid Earth 122(4):2946–2971. https://doi.org/10.1002/2016JB013356

Matoza RS, Fee D, Green DN, Le Pichon A, Vergoz J, Haney MM, Mikesell TD, Franco L, Valderrama OA, Kelley MR, McKee K, Ceranna L (2018) Local, regional, and remote seismo-acoustic observations of the April 2015 VEI 4 eruption of Calbuco Volcano, Chile. J Geophys Res Solid Earth 123(5):3814–3827. https://doi.org/10.1002/2017JB015182

Matoza RS, Fee D, Garcés MA, Seiner JM, Ram on PA, Hedlin MA (2009a) Infrasonic jet noise from volcanic eruptions. Geophys Res Lett 36(8). https://doi.org/10.1029/2008GL036486

Matoza RS, Garcés MA, Chouet BA, D'Auria L, Hedlin MA, De Groot-Hedlin C, Waite GP (2009b) The source of infrasound associated with long-period events at Mount St. Helens. J Geophys Res Solid Earth 114(4). https://doi.org/10.1029/2008JB006128

Matoza RS, Fee D, Green D, Mialle P (2019) Volcano infrasound and the International Monitoring System. In: Infrasound Monitoring for Atmospheric Studies: Challenges in Middle Atmosphere Dynamics and Societal Benefits: Second Edition, Springer International Publishing, pp 1023–1077. https://doi.org/10.1007/978-3-319-75140-5_33

McKee K, Fee D, Yokoo A, Matoza RS, Kim K (2017) Analysis of gas jetting and fumarole acoustics at Aso Volcano, Japan. J Volcanol Geotherm Res. https://doi.org/10.1016/j.jvolgeores.2017.03.029

McKee K, Fee D, Haney M, Matoza RS, Lyons J (2018) Infrasound signal detection and back azimuth estimation using ground-coupled airwaves on a seismo-acoustic sensor pair. J Geophys Res Solid Earth 123(8):6826–6844. https://doi.org/10.1029/2017JB015132

McKee K, Smith CM, Reath K, Snee E, Maher S, Matoza RS, Carn S, Mastin L, Anderson K, Damby D, Roman DC, Degterev A, Rybin A, Chibisova M, Assink JD, de Negri LR, Perttu A (2021a) Evaluating the state-of-the-art in remote volcanic eruption characterization Part I: Raikoke volcano, Kuril Islands. J Volcanol Geoth Res 419:107354. https://doi.org/10.1016/j.jvolgeores.2021.107354

McKee K, Smith C, Reath K, Snee E, Maher S, Matoza RS, Carn S, Roman DC, Mastin L, Anderson K, Damby D,, Itikarai I, Mulina K, Saunders S, Assink J, de Negri Leiva R, Perttu A. (2021b) Evaluating the State-of-the-Art in Remote Volcanic Eruption Characterization Part II: Ulawun Volcano, Papua New Guinea, Journal of Volcanology and Geothermal Research, 420. https://doi.org/10.1016/j.jvolgeores.2021.107381

McNutt SR, Thompson G, Johnson J, De Angelis S, Fee D (2015) Seismic and infrasonic monitoring. In: The encyclopedia of volcanoes, Academic Press, pp 1071–1099. https://doi.org/10.1016/B978-0-12-385938-9.00063-8.

Medici EF, Allen JS, Waite GP (2014) Modeling shock waves generated by explosive volcanic eruptions. Geophys Res Lett 41:414–421. https://doi.org/10.1002/2013GL058340

Méndez-Harper JS, Cimarelli C, Dufek J, Gaudin D, Thomas RJ (2018) Inferring compressible fluid dynamics from vent discharges during volcanic eruptions. Geophys Res Lett 45(14):7226–7235. https://doi.org/10.1029/2018GL078286

Minasny B, Fiantis D, Mulyanto B, Sulaeman Y, Widyatmanti W (2020) Global soil science research collaboration in the 21st century: Time to end helicopter research. Geoderma 373:114299. https://doi.org/10.1016/j.geoderma.2020.114299

Moran SC, Matoza RS, Garcés MA, Hedlin MAH, Bowers D, Scott WE, Sherrod DR, Vallance JW (2008) Seismic and acoustic recordings of an unusually large rockfall at Mount St. Helens, Washington. Geophys Res Lett 35(19):L19302. https://doi.org/10.1029/2008GL035176

Morrissey MM, Chouet BA (1997) Burst conditions of explosive volcanic eruptions recorded on microbarographs. Science 275(5304):1290–1293. https://doi.org/10.1126/science.275.5304.1290

Nishida K, Ichihara M (2016) Real-time infrasonic monitoring of the eruption at a remote island volcano using seismoacoustic cross correlation. Geophys J Int 204(2):748–752. https://doi.org/10.1093/gji/ggv478

Ogden DE, Wohletz KH, Glatzmaier GA, Brodsky EE (2008) Numerical simulations of volcanic jets: importance of vent overpressure. J Geophys Res 113:B02204. https://doi.org/10.1029/2007JB005133

Ortiz HD, Johnson JB, Ramón PG, Ruiz MC (2018) Using infrasound waves to monitor tropospheric weather and crater morphology changes at Volcán Tungurahua, Ecuador. J Volcanol Geoth Res 349:205–216. https://doi.org/10.1016/j.jvolgeores.2017.11.001

Ortiz HD, Matoza RS, Garapaty C, Rose K, Ramón P, Ruiz MC (2020) Multiyear regional infrasound detection of Tungurahua, El Reventador, and Sangay volcanoes in Ecuador from 2006 to 2013. In: 179th Meeting of the Acoustical Society of America, ASA, vol 42, p 022003. https://doi.org/10.1121/2.0001362

Patrick MR, Dietterich HR, Lyons JJ, Diefenbach AK, Parcheta C, Anderson KR, Namiki A, Sumita I, Shiro B, Kauahikaua JP (2019) Cyclic lava effusion during the 2018 eruption of Kilauea Volcano. Science 366(6470), DOI https://doi.org/10.1126/science.aay9070

Peña Fernández JJ, Cigala V, Kueppers U, Sesterhenn J (2020) Acoustic analysis of starting jets in an anechoic chamber: implications for volcano monitoring. Sci Rep 10(1):1–12. https://doi.org/10.1038/s41598-020-69949-1

Perttu A, Taisne B, De Angelis S, Assink JD, Tailpied D, Williams RA (2020a) Estimates of plume height from infrasound for regional volcano monitoring. J Volcanol Geoth Res 402:106997. https://doi.org/10.1016/j.jvolgeores.2020.106997

Perttu A, Caudron C, Assink JD, Metz D, Tailpied D, Perttu B, Hibert C, Nurfiani D, Pilger C, Muzli M, Fee D, Anderson OL, Taisne B (2020b) Reconstruction of the 2018 tsunamigenic flank collapse and eruptive activity at Anak Krakatau based on eyewitness reports, seismo-acoustic and satellite observations. Earth Planet Sci Lett 541:116268. https://doi.org/10.1016/j.epsl.2020.116268

Petersen T, McNutt SR (2007) Seismo-acoustic signals associated with degassing explosions recorded at Shishaldin volcano, Alaska, 2003–2004. Bull Volcanol 69:527–536. https://doi.org/10.1007/s00445-006-0088-z

Richardson JP, Waite GP, Palma JL (2014) Varying seismic-acoustic properties of the fluctuating lava lake at Villarrica, Chile. J Geophys Res Solid Earth 119(7):5560–5573. https://doi.org/10.1002/2014JB011002

Ripepe M, Ciliberto S, Della Schiava M (2001) Time constraints for modeling source dynamics of volcanic explosions at Stromboli. J Geophys Res Solid Earth 106(B5):8713–8727. https://doi.org/10.1029/2000JB900374

Ripepe M, Harris AJ, Carniel R (2002) Thermal, seismic and infrasonic evidences of variable degassing rates at Stromboli volcano. J Volcanol Geoth Res 118(3–4):285–297. https://doi.org/10.1016/S0377-0273(02)00298-6

Ripepe M, Marchetti E, Ulivieri G (2007) Infrasonic monitoring at Stromboli volcano during the 2003 effusive eruption: Insights on the explosive and degassing process of an open conduit system. J Geophys Res Solid Earth 112:B9. https://doi.org/10.1029/2006JB004613

Ripepe M, Bonadonna C, Folch A, Delle Donne D, Lacanna G, Marchetti E, Höskuldsson A (2013) Ash-plume dynamics and eruption source parameters by infrasound and thermal imagery: the 2010 Eyjafjallajökull eruption. Earth Planet Sci Lett 366:112–121. https://doi.org/10.1016/j.epsl.2013.02.005

Ripepe M, Marchetti E, Delle Donne D, Genco R, Innocenti L, Lacanna G, Valade S (2018) Infrasonic early warning system for explosive eruptions. J Geophys Res Solid Earth 123(11):9570–9585. https://doi.org/10.1029/2018JB015561

Ripepe M, Marchetti E (2019) Infrasound monitoring of volcano-related hazards for civil protection. In: Infrasound Monitoring for Atmospheric Studies: Challenges in Middle Atmosphere Dynamics and Societal Benefits: Second Edition, Springer International Publishing, pp 107–1140. https://doi.org/10.1007/978-3-319-75140-5_35

Ripepe M, Marchetti E, Bonadonna C, Harris AJ, Pioli L, Ulivieri G. (2010a) Monochromatic infrasonic tremor driven by persistent degassing and convection at Villarrica Volcano, Chile. Geophys Res Lett 37(15). https://doi.org/10.1029/2010GL043516.

Ripepe M, De Angelis S, Lacanna G, Voight B (2010b) Observation of infrasonic and gravity waves at Soufriere Hills Volcano, Montserrat. Geophysical Research Letters 37. https://doi.org/10.1029/2010GL042557

Sahetapy-Engel ST, Harris AJL, Marchetti E (2008) Thermal, seismic and infrasound observations of persistent explosive activity and conduit dynamics at Santiaguito lava dome, Guatemala. J Volcanol Geoth Res 173(1–2):1–14. https://doi.org/10.1016/j.jvolgeores.2007.11.026

Sanderson RW, Matoza RS, Fee D, Haney MM, Lyons JJ (2020) Remote detection and location of explosive volcanism in alaska with the earthscope transportable array. J Geophys Res Solid Earth 125(4):1–23. https://doi.org/10.1029/2019JB018347

Sanderson RW, Matoza RS, Haymon RM, Steidl JH (2021) A Pilot Experiment on Infrasonic Lahar Detection at Mount Adams, Cascades: Ambient Infrasound and Wind-Noise Characterization at a Quiescent Stratovolcano. Seismological Research Letters. https://doi.org/10.1785/0220200361

Schmid M, Kueppers U, Cigala V, Sesterhenn J, Dingwell DB (2020) Release characteristics of overpressurised gas from complex vents: implications for volcanic hazards. Bull Volcanol 82(68). https://doi.org/10.1007/s00445-020-01407-2

Schwaiger HF, Iezzi AM, Fee D (2019) AVO-G2S: A modified, open-source Ground-to-Space atmospheric specification for infrasound modeling. Comput Geosci 125:90–97. https://doi.org/10.1016/j.cageo.2018.12.013

Schwaiger HF, Lyons JJ, Iezzi AM, Fee D, Haney MM (2020) Evolving infrasound detections from Bogoslof volcano, Alaska: insights from atmospheric propagation modeling. Bull Volcanol 82(3):1–14. https://doi.org/10.1007/s00445-020-1360-3

Smith CM, Thompson G, Reader S, Behnke SA, McNutt SR, Thomas R, Edens H (2020) Examining the statistical relationships between volcanic seismic, infrasound, and electrical signals: a case study of Sakurajima volcano, 2015. Journal of Volcanology and Geothermal Research. 402. https://doi.org/10.1016/j.jvolgeores.2020.106996

Stall S, Yarmey L, Cutcher-Gershenfeld J, Hanson B, Lehnert K, Nosek B, Parsons M, Robinson E, Wyborn L (2019) Make scientific data FAIR. Nature. https://doi.org/10.1038/d41586-019-01720-7

Steffke AM, Fee D, Garces M, Harris A (2010) Eruption chronologies, plume heights and eruption styles at Tungurahua volcano: integrating remote sensing techniques and infrasound. J Volcanol Geoth Res 193(3–4):143–160. https://doi.org/10.1016/j.jvolgeores.2010.03.004

Swanson E, Theunissen R, Rust A, Green D, Phillips J (2018) An experimental study of the flow structure and acoustics of jets: implications for volcano infrasound. J Volcanol Geoth Res 363:10–22. https://doi.org/10.1016/j.jvolgeores.2018.08.005

Taddeucci J, Scarlato P, Capponi A, Del Bello E, Cimarelli C, Palladion DM, Kueppers U (2012) High-speed imaging of strombolian explosions: the ejection velocity of pyroclasts. Geophys Res Lett 39:L02301. https://doi.org/10.1029/2011GL050404

Taddeucci J, Sesterhenn J, Scarlato P, Stampka K, Del Bello E, Pena Fernandez J, Gaudin D (2014) High-speed imaging, acoustic features, and aeroacoustic computations of jet noise from Strombolian (and Vulcanian) explosions. Geophys Res Lett 41:3096–3102. https://doi.org/10.1002/2014GL059925

Taisne B, Perttu A, Tailpied D, Caudron C, Simonini L (2019) Atmospheric controls on ground-and space-based remote detection of volcanic ash injection into the atmosphere, and link to early warning systems for aviation hazard mitigation. In: Infrasound Monitoring for Atmospheric Studies: Challenges in Middle Atmosphere Dynamics and Societal Benefits: Second Edition, Springer International Publishing, pp 1079–1105. https://doi.org/10.1007/978-3-319-75140-5_34

Thelen W, Matoza RS, Hotovec-Ellis A. (2022) Trends in volcano seismology: 2010 to 2020 and beyond. Bull Volcanol 84:26. https://doi.org/10.1007/s00445-022-01530-2

Titos M, Bueno A, García L, Benítez C, Segura JC (2020) Classification of isolated volcano-seismic events based on inductive transfer learning. IEEE Geosci Remote Sens Lett 17(5):869–873. https://doi.org/10.1109/LGRS.2019.2931063

Toney L, Fee D, Allstadt KE, Haney MM, Matoza RS (2021) Reconstructing the dynamics of the highly similar May 2016 and June 2019 Iliamna Volcano (Alaska) ice-rock avalanches from seismoacoustic data. Earth Surf Dyn 9(2):271–293. https://doi.org/10.5194/esurf-9-271-2021

Ulivieri G, Ripepe M, Marchetti E (2013) Infrasound reveals transition to oscillatory discharge regime during lava fountaining: implications for early warning. Geophys Res Lett 40(12):3008–3013. https://doi.org/10.1002/grl.50592

Vergniolle S, Caplan-Auerbach J (2006) Basaltic thermals and subplinian plumes: constraints from acoustic measurements at Shishaldin volcano, Alaska. Bull Volcanol 68:611–630. https://doi.org/10.1007/s00445-005-0035-4

Vergniolle S, Ripepe M (2008) From strombolian explosions to fire fountains at Etna volcano (Italy): what do we learn from acoustic measurements. Geol Soc London Spec Publ 307:103–124. https://doi.org/10.1144/SP307.7

Waite GP, Nadeau PA, Lyons JJ (2013) Variability in eruption style and associated very long period events at Fuego volcano, Guatemala. J Geophys Res Solid Earth 118(4):1526–1533. https://doi.org/10.1002/jgrb.50075

Watson LM (2020) Using unsupervised machine learning to identify changes in eruptive behavior at Mount Etna, Italy. J Volcanol Geoth Res 405:107042. https://doi.org/10.1016/j.jvolgeores.2020.107042

Watson LM, Dunham EM, Johnson JB (2019) Simulation and inversion of harmonic infrasound from open-vent volcanoes using an efficient quasi-1D crater model. J Volcanol Geoth Res 380:64–79. https://doi.org/10.1016/j.jvolgeores.2019.05.007

Watson LM, Johnson JB, Sciotto M, Cannata A (2020) Changes in crater geometry revealed by inversion of harmonic infrasound observations: 24 December 2018 eruption of Mount Etna, Italy. Geophysical Research Letters 47. https://doi.org/10.1029/2020GL088077

Watson LM, Dunham EM, Mohaddes D, Labahn J, Jaravel T, Ihme M (2021a) Infrasound radiation from impulsive volcanic eruptions: nonlinear aeroacoustic 2D simulations. J Geophys Res Solid Earth:126. https://doi.org/10.1029/2021JB021940

Watson LM, Carpenter B, Thompson K, Johnson JB (2021b) Using local infrasound arrays to detect plunging snow avalanches along the Milford Road, New Zealand (Aotearoa). Nat Hazards. https://doi.org/10.1007/s11069-021-05086-w

Waxler R, Assink J, Velea D (2017) Modal expansions for infrasound propagation and their implications for ground-to-ground propagation. J Acoust Soc Am 141(2):1290–1307. https://doi.org/10.1121/1.4976067

Waxler R, Hetzer C, Velea D (2015) Atmospheric Infrasound Propagation Package Version 1.1: Extension and Finalization

Wilson G, Bryan J, Cranston K, Kitzes J, Nederbragt L, Teal TK (2017) Good enough practices in scientific computing. PLoS Comput Biol 13(6):e1005510. https://doi.org/10.1371/journal.pcbi.1005510

Wilson DC, Davis P, Ebeling C, Hutt CR, Hafner K (2018). Seismic sensors record a hurricane's roar. Eos, Earth and Space Science News, 99. https://doi.org/10.1029/2018EO102963

Witsil AJC, Johnson JB (2020) Analyzing continuous infrasound from Stromboli volcano, Italy using unsupervised machine learning. Comput Geosci. https://doi.org/10.1016/j.cageo.2020.104494

Woulff G, McGetchin TR (1976) Acoustic noise from volcanoes - Theory and experiment. Geophys J Roy Astron Soc 45:601–616. https://doi.org/10.1111/j.1365-246X.1976.tb06913.x

Yamada T, Aoyama H, Nishimura T, Iguchi M, Hendrasto M (2017) Volcanic eruption volume flux estimations from very long period infrasound signals. Geophys Res Lett 44(1):143–151. https://doi.org/10.1002/2016GL071047

Yamada T, Ueda H, Mori T, Tanada T (2019) Tracing volcanic activity chronology from a multiparameter dataset at Shinmoedake volcano (Kirishima), Japan. J Disaster Res 14(5):687–700. https://doi.org/10.20965/jdr.2019.p0687

Yamasato H (1997) Quantitative analysis of pyroclastic flows using infrasonic and seismic data at Unzen volcano, Japan. J Phys Earth 45(6):397–416. https://doi.org/10.4294/jpe1952.45.397

Yokoo A, Ishihara K (2007) Analysis of pressure waves observed in Sakurajima eruption movies. Earth, Planets and Space 59:177–181. https://doi.org/10.1186/BF03352691

Yokoo A, Tameguri T, Iguchi M (2009) Swelling of a lava plug associated with a vulcanian eruption at Sakurajima volcano, Japan, as revealed by infrasound record: case study of the eruption on January 2, 2007. Bull Volcanol 71:619–630. https://doi.org/10.1007/s00445-008-0247-5

Yokoo A, Iguchi M, Tameguri T, Yamamoto K (2013) Processes Prior to Outbursts of Vulcanian Eruption at Showa Crater of Sakurajima Volcano (Sakurajima Special Issue). Bull Volcanol Soc Japan 58(1):163–181. https://doi.org/10.18940/kazan.58.1_163