



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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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; Vergnolle & 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., Vergnolle & 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

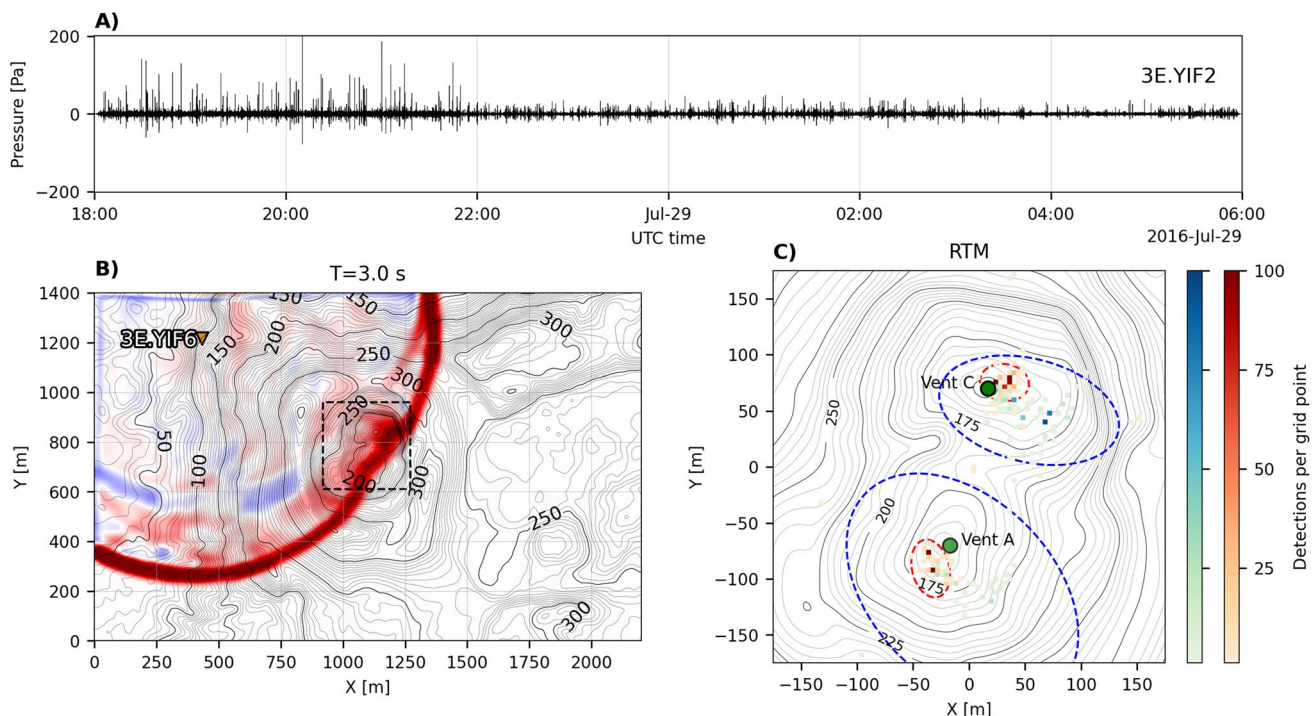


Fig. 1 Demonstration of the substantial effect of topography on the infrasonic wavefield and infrasound-derived locations at Yasur volcano, Vanuatu. **A** Twelve hours of infrasound data from a station deployed on the crater rim. Multiple explosions occur every minute. **B** Finite-difference time domain (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 histo-

grams 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.

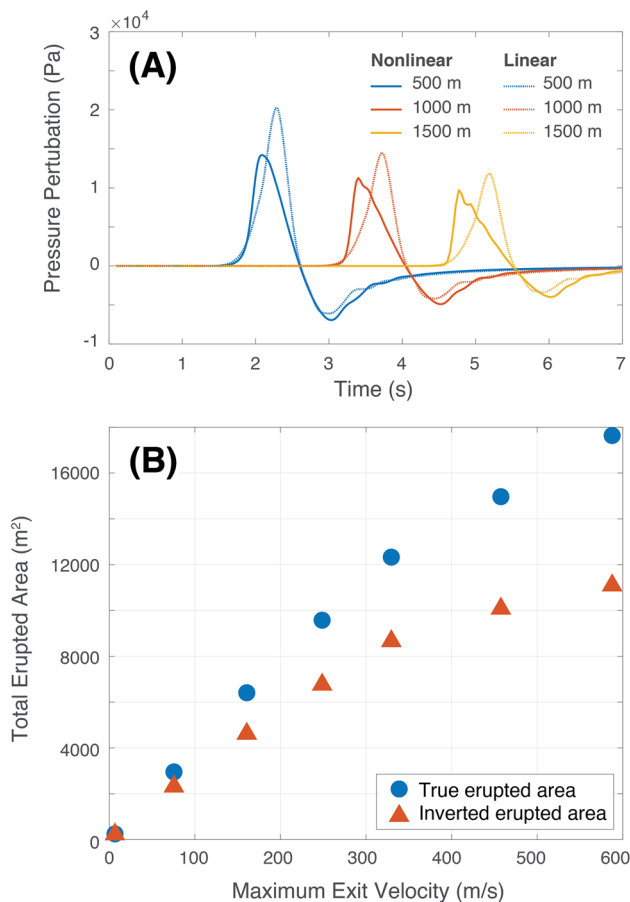


Fig. 2 **A** Comparison of synthetic infrasound signals from 2-D nonlinear aeroacoustic simulations (solid lines) and predictions based on linear monopole source model (dashed lines) at three different recording distances (blue, 500 m; red, 1000 m; yellow, 1500 m) for a maximum exit velocity of 588 m/s. 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; Sander-son 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

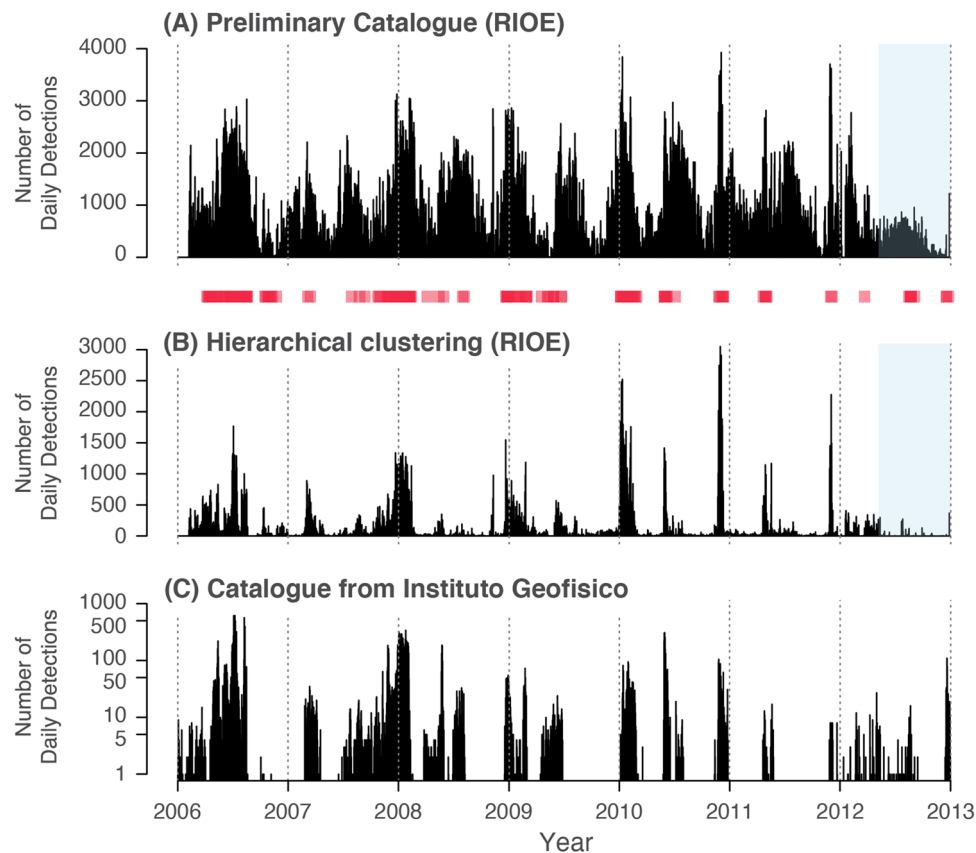


Fig. 3 Unsupervised machine learning applied to infrasound data from RIOE array, which is 37 km from Tungurahua. **A** Preliminary catalog showing the number of daily detections of signals originating within $\pm 10^\circ$ of the expected back-azimuth (33°) to Tungurahua. **B** Daily count of impulsive 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, SO₂ 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 m³/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 SO₂, 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 SO₂ 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).

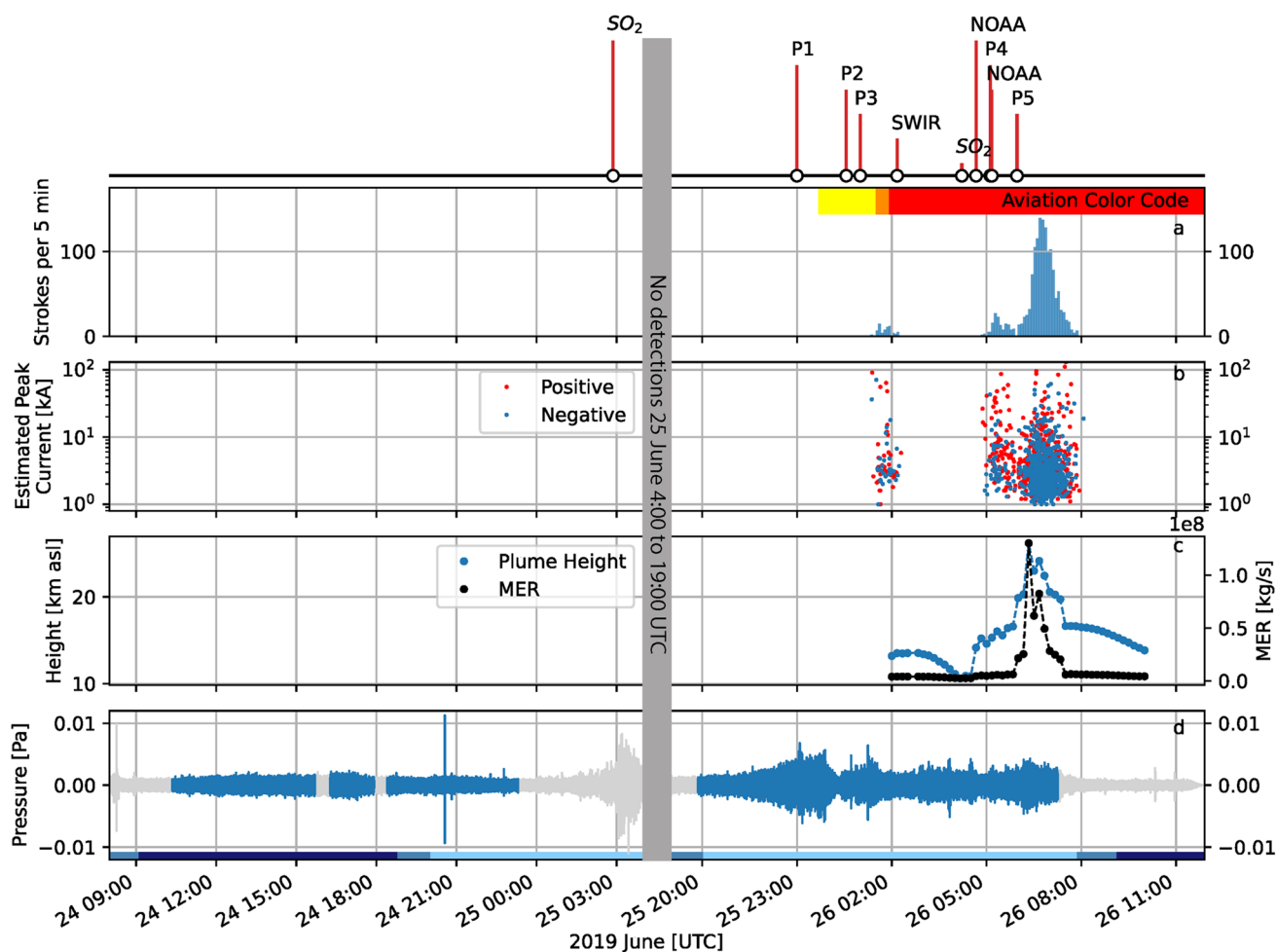


Fig. 4 Ulawun eruption sequence observations comparing discrete (red lines at top; SO₂, pilot photos, NOAA ash plume detections, and shortwave infrared satellite (SWIR) observations) and time series (lightning, plume height, mass eruption rate (MER), infrasound) observations. **A** Lightning strokes per 5 min, **B** estimated peak cur-

rent 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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