

13 July 2026

Stratospheric balloon observations of infrasound from the 2021-2022 Hunga eruptive sequence and its 19 December 2021 eruption

Paul Hardy¹, Aurélien Podglajen², Alexis Le Pichon³, Constantino Listowski⁴, Albert Hertzog⁵, Sophus Bredesen Gullbekk⁶, Marouchka Froment⁷, Sven Peter Näsholm⁸, Quentin Brissaud⁹, Lucie Schwoebel¹⁰

1. Laboratoire de météorologie dynamique, Ecole Polytechnique

2. Laboratoire de météorologie dynamique, Ecole Polytechnique

3. CEA, DAM, DIF

4. CEA

5. Laboratoire de météorologie dynamique

6. NORSAR

7. NORSAR

8. NORSAR

9. NORSAR

10. CEA, DAM, DIF

Keywords

Balloon-borne infrasound measurements, Hunga eruptive sequence, Volcanique eruption monitoring, Infrasound propagation modeling, Gravity waves

Stratospheric balloon observations of infrasound from the 2021–2022 Hunga eruptive sequence and its 19 December 2021 eruption

Paul Hardy¹, Aurélien Podglajen¹, Alexis Le Pichon², Constantino Listowski²,
Albert Hertzog³, Sophus Bredeesen Gullbekk⁴, Marouchka Froment⁴, Sven
Peter Näsholm^{4,5}, Quentin Brissaud⁴, and Lucie Schwoebel²

¹Laboratoire de Météorologie Dynamique (LMD/IPSL), École Polytechnique, Institut Polytechnique de
Paris, Sorbonne Université, École Normale Supérieure, PSL Research University, CNRS, Paris, France

²CEA, DAM, DIF, F-91297 Arpajon, France

³Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Université, École polytechnique,
Institut polytechnique de Paris, École normale supérieure, PSL Research University, CNRS, Paris, France

⁴NORSAR, Kjeller, Norway

⁵Department of Informatics, University of Oslo, Oslo, Norway

Key Points:

- Strateole-2 balloons provided continuous low-noise infrasound measurements of Hunga’s December 2021-January 2022 eruptive sequence
- All balloons observed coherent signals emitted by the moderate 19 December eruption, in contrast with heterogeneous ground-based detections
- Simulated attenuation is overestimated for a ground source, the best fit is achieved for a source in the volcanic plume above 10 km altitude

Corresponding author: P. Hardy, paul.hardy@lmd.ipsl.fr

Abstract

Balloon-borne infrasound monitoring has undergone a revival over the past decade, driven by technological advances that enable high-sensitivity, low-noise acoustic recordings from air-borne platforms. The cataclysmic 15 January 2022 Hunga Tonga eruption demonstrated the exceptional infrasound detection capabilities of stratospheric balloons, but the advantages for monitoring more common eruptions remain unassessed. This study evaluates the potential of balloon-borne measurements for volcanic monitoring by analysing the entire December 2021–January 2022 Hunga Tonga eruptive sequence using observations from five Strateole-2 superpressure balloons and the International Monitoring System (IMS) ground-based infrasound network. Balloon records reveal the full chronology of the sequence, showing excellent agreement with satellite and seismic data, and even clarifying ambiguous plume timings. A detailed analysis of the moderate initial eruption on 19 December 2021 demonstrates a key advantage: all in-flight balloons detected a clear and coherent long duration signal, whereas ground-based IMS stations exhibited uneven and noise-limited detection capabilities. While parabolic equation-based infrasound propagations simulations using a volcano-level source reproduce signal celerities reliably, they drastically overestimate the anisotropy in acoustic amplitudes, predicting excessive amplitudes in downwind directions compared to observations. We show that simulating an elevated source within the volcanic umbrella cloud (10–15 km) reduces this anisotropy and yields better agreement with recorded amplitudes, highlighting the importance of the eruption-generated plume as an acoustic source. These findings underscore the added value of balloon-borne sensors for the reliable monitoring of moderate volcanic eruptions, providing insights that are not readily accessible from ground-based networks alone.

Plain Language Summary

Over the past decade, balloons have been used to listen to low-frequency sounds (infrasound) produced by geophysical events. The huge eruption of Hunga Tonga (Hunga) on 15 January 2022 showed that balloons are excellent at detecting infrasounds. However, we did not know if balloons would be useful for monitoring common eruptions. In this study, we tested the ability of balloon-borne sensors to monitor eruptions by examining the entire eruptive sequence from Hunga between December 2021 and January 2022. We compared data from stratospheric balloons with data from ground-based stations. We found that the balloons provided a clear timeline of the eruptive sequence, matching satellite and seismic measurements. The study of the moderate eruption on 19 December showed that every balloon detected a clear signal where ground stations had trouble detecting as precisely the event due to wind-induced acoustic noise at the ground, establishing balloons as a valuable addition to ground-based infrasound networks. Interestingly, simulations predicted reliably the sound speed, but they overestimated how much the sound amplitude varied with direction of propagation. The results improve by placing the acoustic source above the volcano’s altitude, inside the volcanic plume (10–15 km altitude) in simulations, suggesting that the plume is an acoustic source.

1 Introduction

Balloon-borne measurements for infrasound monitoring studies began in the late 1940s following World War II. The initial measurements were conducted for military purposes and involved advanced balloon technology (D. Bowman et al., 2019). Apart from a few studies in the 1960s and 1990s concerning the estimation of arrival direction (Wescott, 1964), background noise characterisation (Coffman, 1965) and explosion detection (Banister & Hereford, 1991), balloon-borne infrasound measurements were rarely used or studied for half a century. Reduced wind-induced acoustic noise and the ability to place balloons in elevated acoustic wave ducts (Albert et al., 2023), together with developments in method and technology in the early 2010s, led to renewed interest in balloon-borne measurements

for geophysical events monitoring, especially infrasound monitoring (Young et al., 2018). Since then, flying sensors as stratospheric balloons have regularly been used to detect and to characterise various events, like earthquakes (Brissaud et al., 2021; Garcia et al., 2022; Froment et al., 2025), explosions (D. C. Bowman & Krishnamoorthy, 2021) and fireworks (Saito et al., 2026). Balloon-borne infrasound measurements also appear to hold great promise for extraterrestrial exploration, particularly in the case of Venus seismicity (Garcia et al., 2024; Brissaud et al., 2025).

Infrasound monitoring has proved valuable in studying volcanic eruptions and distinguishing between different types of volcanic activity (Johnson & Ripepe, 2011; Watson et al., 2022). The infrasound stations on the ground of the International Monitoring System (IMS) enabled the study of the last eruptive sequence of the Hunga Tonga (Hunga) volcano (Kingdom of Tonga) that began on 19 December 2021 and ended on 15 January 2022, culminating in an exceptionally powerful event, unseen since the eruption of the Krakatoa volcano in 1883 (Matoza et al., 2022), whose impact is still a current topic of research (Zhu et al., 2025; Wilmouth et al., 2023; Duchamp et al., 2025; Kloss et al., 2025).

The dominant Lamb wave and the broadband acoustic-gravity waves generated by the cataclysmic eruption on 15 January 2022 were detected around the world by the 53 IMS infrasound stations and their observations provided key constraints on the eruptive source, particularly regarding its temporal sequence, source mechanism, and energy release with an equivalent yield estimated of the order of 100–200 Mt TNT (Matoza et al., 2022; Vergoz et al., 2022). The acoustic waves generated by this eruption were also monitored by Strateole-2 (ST2) stratospheric superpressure balloons flying thousands of kilometres from Hunga. The ST2 campaign was intended to study the tropical upper troposphere lower stratosphere (UTLS) using superpressure balloons carrying pressure sensors that detected the generated infrasound. Podglajen et al. (2022) demonstrated that the ST2 balloons detected more global wave revolutions than most ground stations, and with a higher signal-to-noise ratio (SNR). The unprecedented power of this eruption introduced uncertainties, particularly regarding the vertical distribution of the acoustic source, and the benefits of balloon-borne measurements for long range volcanic infrasound monitoring assessed by Podglajen et al. (2022) cannot be extended to less energetic events. The aim of this paper is twofold: to provide an overview of the entire 2021–2022 Hunga eruptive sequence while focusing on the initial event of 19 December 2021 using both stratospheric balloon-borne and ground-based infrasound measurements and to assess the capability of balloon-borne measurements for monitoring volcanic eruptions of moderate intensity.

The paper is organized as follows. First, an overview of the entire 2021–2022 Hunga eruptive sequence based on balloon-borne infrasound observations is presented. Then, balloon observations of the 19 December 2021 eruption are analyzed together with ground-based records from the IMS infrasound stations. Combined with parabolic-equation based wave propagation simulations, observations are used to reconstruct the eruption chronology and to compare propagation characteristics between ground-based receivers and those at balloon altitude. Finally, combining observations and simulations allows us to examine the vertical distribution of the acoustic source and to assess differences in SNR and detection capability between ground-based and upper-air sensors.

2 Data and Methods

2.1 Infrasound observations

2.1.1 *Strateole-2 balloon data*

In the framework of the ST2 balloon project, seventeen superpressure balloons were launched from the Seychelles between October and December 2021 by the French space

agency (CNES) to study the tropical UTLS (Hertzog & Plougonven, 2021; *Stratéole-2 C1 campaign dataset*, 2021). ST2 superpressure balloons are constant-volume balloons drifting horizontally with the wind for several months at a chosen level (near 18.5 km or 20.5 km altitude in the tropics). At the onset of the Hunga eruptive sequence on 19 December 2021 (Vergoz et al., 2022), five ST2 balloons were still flying over the tropical Pacific. Their location at that time is represented in Figure 1. Of those five balloons, only two flew throughout the last Hunga eruptive sequence until the climatic eruption on 15 January 2022. Observations from this event were analysed by Podglajen et al. (2022), who demonstrated the capability of high-frequency pressure measurements from balloons to detect geophysical signals. Although the same balloons are used here, we adopt a different naming convention, referring to them according to their launch order rather than their payload configuration as in Podglajen et al. (2022). Thus, balloons *STR1* and *TTL4* in Podglajen et al. (2022) are denoted here as *B13* and *B15*, respectively.

ST2 balloon payloads include two temperature and one pressure sensors (Hertzog et al., 2007) and a GPS measuring position every 30 s with 1 m altitude resolution. The pressure sensor (Paroscientific-6000-15A) samples at 1 Hz with 100 μPa resolution and has a flat frequency response up to 0.25 Hz. Following Podglajen et al. (2022), the fluctuations due to the vertical motion of the balloon in an hydrostatic atmosphere are removed to derive the corresponding constant-altitude pressure perturbation p :

$$p = p_b \exp\left(\frac{g \zeta'}{R_d T_b}\right) - \bar{p}_b \quad (1)$$

where p_b and T_b are the measured raw pressure and temperature, $\bar{p}_b$ the 1-day time-averaged pressure, ζ' geopotential height anomalies derived from GPS altitude interpolated at 1 s, $g = 9.81 \text{ m.s}^{-2}$ and $R_d = 287 \text{ J.K}^{-1}.\text{kg}^{-1}$. The correction given by Equation 1 becomes significant at frequencies comparable to the balloon oscillation frequency ($\sim 4.5 \text{ mHz}$) or below (Massman, 1978; Podglajen et al., 2016; Wilson et al., 2023). For infrasound frequencies above $\sim 0.02 \text{ Hz}$, p closely follows p_b (Podglajen et al., 2022).

2.1.2 IMS microbarometer data

The IMS infrasound network has been developed in the framework of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). In December 2021-January 2022, it comprised 53 certified infrsound ground-based stations that continuously sample differential pressure at a rate of 20 Hz. Eleven IMS stations, located between 1800 and 6000 km from Hunga at various azimuths directions and under different monitoring conditions (against or along the horizontal stratospheric wind, hereafter referred to as upwind and downwind, respectively) and local wind environment are considered in this study (see Figure 1).

Each IMS station consists of an array of at least four microbarometers sensitive to pressure changes down to 1 mPa, with apertures ranging from 1 to 4 km, equipped with wind-noise reduction systems (Marty, 2019). The instrument response is designed for a frequency range of approximately 0.01–5 Hz. Infrasound monitoring capability is limited by local wind and turbulence which are the main sources of noise (Raspet et al., 2019). In the 0.01–0.5 Hz band, infrasound noise generally increases with wind speed by about 5 dB per m s^{-1} (Walker & Hedlin, 2009; Raspet et al., 2019).

The detection capabilities of raw single microbarometer measurements are significantly enhanced by combining sensors through the Progressive Multi-Channel Correlation algorithm (PMCC) (Cansi, 1995; Brachet et al., 2009). PMCC detects coherent wavefronts across an array of sensors by computing cross-correlations in the time–frequency domain and progressively grouping consistent time delays between sensor pairs. This approach provides estimates of detection time, back-azimuth, and apparent velocity by isolating clusters of delays that remain spatially coherent across multiple sensors, thereby enabling the detection of signals up to 5 dB below the noise level of individual channels (Cansi & Pichon, 2008; Poste et al., 2022).

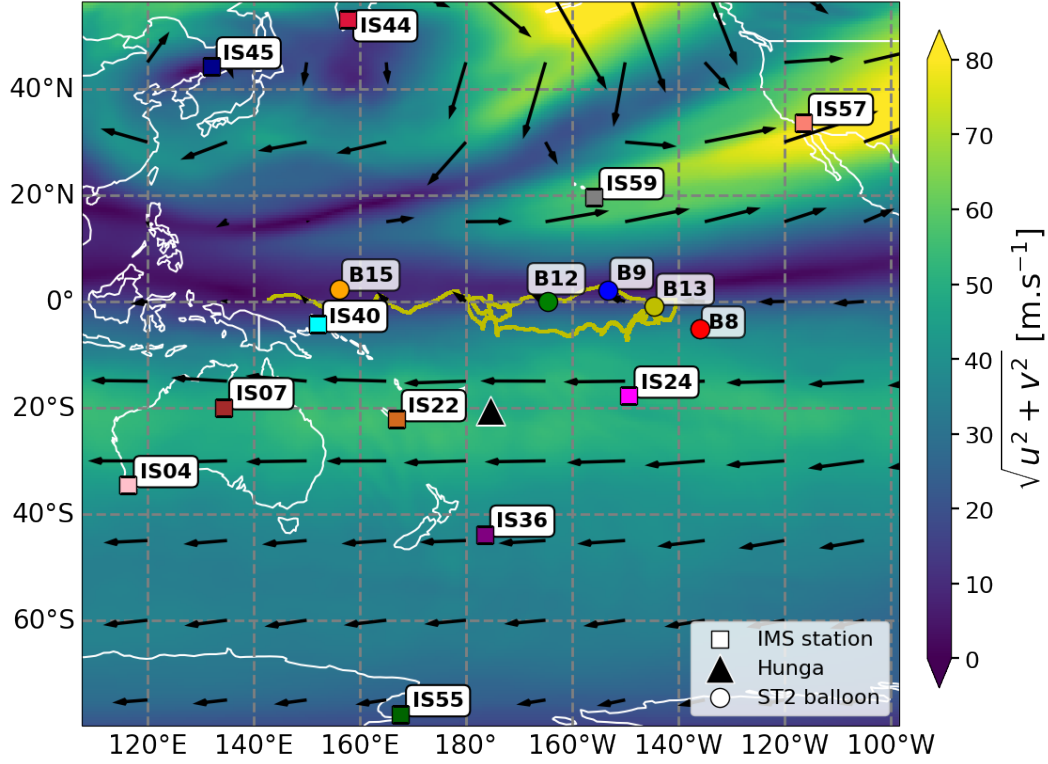


Figure 1. Horizontal wind direction (vectors) and speed (colormap) averaged between 40 and 60 km on 19 December 2021 from ERA5 reanalysis data from the fifth generation ECMWF reanalysis. The trajectory of *B13* from 3 December 2021 to 25 January 2022 (end of flight) is represented as a green line.

In the present study, when estimates of the back-azimuth θ_{PMCC} and phase speed c_{PMCC}^ϕ of the signals from Hunga are provided by PMCC at a station, a delay-and-sum beamforming technique, as described in Rost and Thomas (2002), is applied to the signals from all channels. This coherently stacks the recordings by correcting for the time delays associated with a plane wave propagating with parameters $(\theta_{\text{PMCC}}, c_{\text{PMCC}}^\phi)$. Signal components that are inconsistent with the plane-wave assumption are attenuated, while those that are coherent with it are preserved. Signal to noise ratio of consistent arrivals is theoretically improved by a factor $\sqrt{N}$, where the number of channels N varies between 3 and 8 (Alcoverro & Le Pichon, 2005).

The analysis of the observed signals in the following sections will be based on spectrograms, computed using 500-s Blackman window with 90% overlap, of the ST2 balloons' corrected 1-Hz pressure (see Equation 1) and of the IMS's rephased 20-Hz pressure.

2.1.3 Observed detection time

Here is explained the method used to define the observed wavefront detection time $t_{\text{obs}}^{(i)}$ at sensor i :

For IMS station i , the period of detection is defined as the time interval during which the signal from Hunga is identified by PMCC. The observed detection time $t_{\text{obs}}^{(i)}$ for IMS stations correspond to the start of this interval.

For balloons we first compute a theoretical window of arrivals from a theoretical event at the top of Hunga (0.149 km) at 20:30 UTC (just before the reported time of the 19 December eruption (Vergoz et al., 2022; Gupta et al., 2022; Donner et al., 2023)), following an empirical model of celerity, with celerity values ranging from 240 to 350 m s⁻¹ (Nippres & Green, 2023). We then compute the observed pressure variance $P_{\text{obs}}^{(i)}(t) = \int_{f_{\min}}^{f_{\max}} \hat{p}_{\text{obs}}^{2(i)}(t, f) df$, where $\hat{p}_{\text{obs}}^{2(i)}(t, f)$ is the value of the spectrogram at f of the observed corrected pressure $p_{\text{obs}}^{(i)}(t)$ at balloon i . The frequency range $\Delta f_{\text{sig}} = [f_{\min}, f_{\max}]$ used is discussed in Section 4.1. The background noise is defined as the 15-minute interval preceding the theoretical window of arrivals at balloon i . $\overline{P_{\text{noise}}^{(i)}}$ over this interval defines the mean noise level, while $\sigma_{\text{noise}}^{(i)}$, its standard deviation, characterises the variability of the background noise. The observed detection time $t_{\text{obs}}^{(i)}$ is then defined within the theoretical window of arrivals as:

$$t_{\text{obs}}^{(i)} = \operatorname{argmin} \left\{ P_{\text{obs}}^{(i)}(t) \geq \overline{P_{\text{noise}}^{(i)}} + 10 \sigma_{\text{noise}}^{(i)} \right\} \quad (2)$$

2.2 Modeling infrasound propagation

2.2.1 Parabolic-equation based wave propagation simulations

Infrasound propagation in the atmosphere is controlled by wind speed and direction profiles (Godin, 2002) as well as temperature gradient (Bass et al., 2007). It is often appropriate to apply the effective sound speed approximation to combine these effects into a single quantity, the effective sound speed c_{eff} , defined in Equation 3:

$$c_{\text{eff}}(r, z) = \sqrt{\frac{\gamma R T(r, z)}{M}} + \mathbf{u}(r, z) \cdot \mathbf{n} \quad (3)$$

the first term corresponds to the adiabatic sound speed where r is the distance from the source, z is the geometric altitude, R is the universal gas constant, M is the molar mass of air and the second term corresponds to the wind effect where $\mathbf{u}(r, z)$ is the horizontal wind, and $\mathbf{n}$ is the wave propagation direction.

Under the plane-wave assumption, the shallow angle approximation, and the effective sound speed approximation, the acoustic pressure field generated by a point source

at altitude z_{so} can be modeled using the parabolic equation (PE) framework (Waxler & Assink, 2019). We use the parabolic solver *ePape* from the *NCPAprop* (Waxler et al., 2021a, 2021b) which computes the monochromatic complex transfer function $\tilde{A}(f)$ relating acoustic pressure amplitude relative to the source power at a frequency f . The inputs to *ePape* consist of atmospheric profiles in the direction of propagation of initial azimuth (θ) of temperature (T), wind components (u , v and w), pressure (p) and density (ρ). The output is chosen to be provided on a grid with a horizontal resolution of 1 km and a vertical resolution of 0.5 km. This resolution choice results from a trade-off between the technical limitations of *ePape* and the fineness of the grid.

ePape assumes planar cylindrical geometry and outputs are scaled complex transfer functions $A_{\text{out}}(f, \theta, r, z, z_{\text{so}}) = \tilde{A}(f, \theta, r, z, z_{\text{so}}) / \sqrt{\rho_0(z)}$ where ρ_0 is the background density profile (Waxler et al., 2021a). In this study, we consider long-range propagation and A_c , defined in Equation 4, is introduced to account for Earth's curvature and geometric spreading in spherical geometry, as well as density effects:

$$A_c(f, \theta, r, z, z_{\text{so}}) = \sqrt{\frac{\rho_0(z)}{\rho_r}} \sqrt{\frac{r \sin(d/a)}{d \sin(r/a)}} A_{\text{out}}(f, \theta, r, z, z_{\text{so}}) \quad (4)$$

where ρ_r is a density of reference at the ground, $a = 6378$ km is the Earth's radius and $d = 1$ km the reference distance to the source. At the propagation distances considered (8000 km or less), the bias corrected by the geometric factor $\sqrt{\frac{r \sin(d/a)}{d \sin(r/a)}}$ is on the order of 10% or lower.

2.2.2 Atmospheric specifications

Wind and temperature profiles required as inputs to *ePape* are derived from hourly ERA5 reanalysis data from the fifth generation ECMWF reanalysis (Hersbach et al., 2020, 2023), extending up to the model upper boundary at approximately 80 km above sea level. Geometric altitude (z), p and ρ on model levels are computed using surface geopotential (Φ_s) and specific humidity (q) (Copernicus Climate Change Service, 2020). From the ERA5 upper boundary up to an altitude of 130 km, u and v are obtained from HWM14 (Drob et al., 2015; Ilma, 2017) and T and ρ from NRLMSISE-00 (Picone et al., 2002; Lucas, 2025). Above ERA5's upper boundary, p is deduced from ideal gas law assuming the adiabatic index $\gamma = \frac{C_p}{C_v} = 7/5$ and $M = 28.965 \times 10^{-3}$ kg.mol⁻¹. The two parts are linked by a 10 km transition layer using cubic interpolation.

Infrasound are sensitive to gravity wave-induced wind and temperature perturbations, which cause partial reflexions of acoustic energy (Hedlin & Drob, 2014; Listowski et al., 2025) and gravity wave may alter geometric acoustic guiding (Kristoffersen et al., 2026). In this study, gravity wave perturbation profiles are built based on a universal spectrum approach. Inverse Fourier transform of gravity wave vertical spectra following the analytical model presented in Gardner et al. (1993) are performed, as explained in Appendix A of Cameijo et al. (2025). Resulting profiles are superimposed onto the wind and temperature atmospheric profiles. These stochastic realizations are not specific to any particular region or time period, but provide a statistical representation of unresolved gravity-wave-induced variability.

2.2.3 Monochromatic transmission loss

Monochromatic transmission loss T_L at a frequency f in the direction θ for a source at z_{so} , relatively to A_c at a reference point (d, z_{so}) is computed using:

$$T_L(f, \theta, r, z, z_{\text{so}}) = 20 \log_{10} \left(\frac{|A_c(f, \theta, r, z, z_{\text{so}})|}{|A_c(f, \theta, r = d, z = z_{\text{so}}, z_{\text{so}})|} \right) \quad (5)$$

T_L maps at 0.1 Hz at ground level and at $z = 20.5$ km (balloon altitude) are shown in Figure 2 (a, b) to illustrate propagation and detection conditions around Hunga on 19 December 2021. These conditions are representative of this region and time period. The simulations are performed for θ sampled every 1° , using atmospheric profiles corresponding to the time of the eruption of 19 December 2021, without added gravity-wave perturbations and with $z_{so} = 0.149$ km (Hunga’s top altitude).

In Figure 2 (a), at the surface in the downwind sector (200° - 330°), a weakly attenuated region (-40 to -60 dB) is predicted, associated with a stratospheric duct. Upwind of Hunga (30° - 150° , extending up to ~ 2000 km), attenuation is weak on average (around -50 dB), with alternating bands of weak and strong attenuation forming fringes spaced by approximately 300 km. Downwind of Hunga, similar fringe patterns are present but with a reduced spacing of about 200 km. These structures correspond to arrivals guided by thermospheric and stratospheric ducts, respectively, and are associated with shadow zones that strongly influence ground-level detections. Within the upwind sector (20° - 60° and 120° - 150°), locally reduced attenuation is attributed to the presence of stratospheric and/or tropospheric ducting. In contrast, outside these regions upwind, surface attenuation drops below -110 dB.

In Figure 2 (b), at balloon altitude, the weakly attenuated downwind region is less clearly defined than at ground level and exhibits slightly higher attenuation (-60 to -70 dB). On both sides of Hunga, the alternating arrivals associated with thermospheric and stratospheric ducts, as well as their corresponding shadow zones, are significantly less pronounced. Upwind (0° - 200°), except within approximately 2000 km of Hunga, attenuation is relatively constant at around -85 dB. The two upwind regions of reduced attenuation identified at ground level are less distinct at balloon altitude.

IMS stations and ST2 balloons are classified in the following as downwind or upwind depending on if the direction of propagation from Hunga to the sensor is along or against the horizontal stratospheric winds (40 to 60 km), so whether or not a stratospheric duct is established.

2.2.4 Waveform reconstruction from monochromatic simulations

To compare simulations and observations across different sensors and to interpret the temporal sequence, full acoustic pressure waveforms are required. The waveforms $p_{\text{sim}}(t, r, z, z_{so})$ are computed from the monochromatic calculations of A_c using Equation 6, derived from Waxler et al. (2021a):

$$p_{\text{sim}}(t, r, z, z_{so}) = \Re \left(\int_{-\infty}^{+\infty} s(f) A_c(f, r, z, z_{so}) \exp(i2\pi f(t + \tau_0)) df \right) \quad (6)$$

where $s(f)$ is the Fourier transform of a Morlet wavelet’s real part considered as the acoustic source function defined by Equation 7 and $\tau_0 = r/c_0$ is a time shift applied to align the signal with a reference sound speed at $c_0 = 400 \text{ m s}^{-1}$.

$$s(f) = \int_{-\infty}^{+\infty} \left(\left(\frac{2\sqrt{\pi}}{15} \right)^{\frac{1}{2}} \exp \left(- \left(\frac{2\pi t}{15\sqrt{2}} \right)^2 \right) \cos \left(\frac{\pi t}{5} \right) \right) \exp(-i2\pi f t) dt \quad (7)$$

In practice, a discrete form of Equation 6 is used, with A_c evaluated over $\Delta f_{\text{sim}} = [0.08, 0.15]$ Hz using a frequency step of 1×10^{-4} Hz. This frequency band and frequency step are chosen to cover Δf_{sig} (see Section 4.1) and to avoid aliasing multiple arrivals in the waveform while accounting for simulation constraints. If $f \notin \Delta f_{\text{sim}}$, we set $A_c(f)$ to 0. We enforce Hermitian symmetry by setting for $f < 0$, $A_c(f) = A_c(-f)^*$ where $A_c(-f)^*$ is the complex conjugation of $A_c(-f)$.

To compute the simulated wavefront celerities $c_{\text{sim}}^{(i)}$ at sensor i we follow a method similar to that used for the observations (see Section 2.1.3).

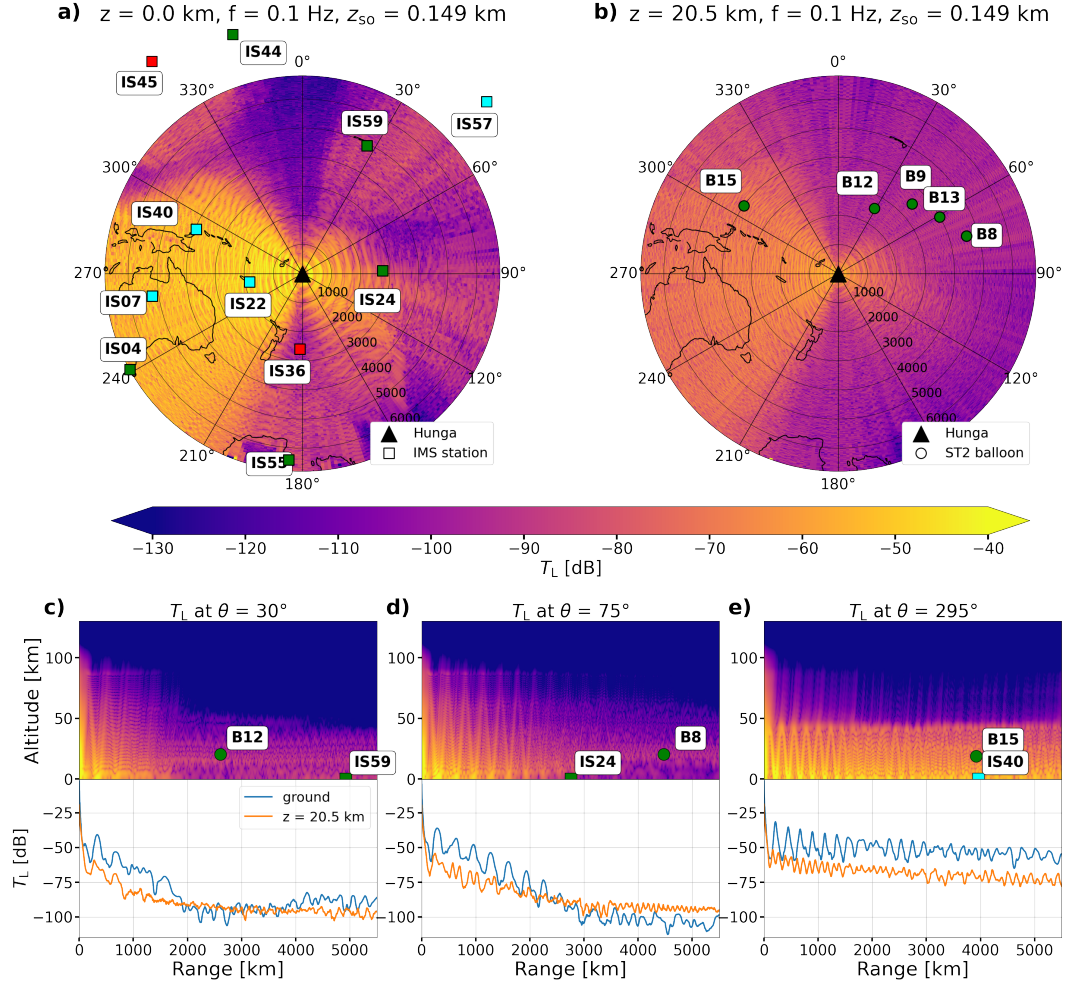


Figure 2. $T_L(f = 0.1$ Hz, $r, z, z_{so} = 0.149$ km) maps centred on Hunga (black triangle) at the ground (a) and at $z = 20.5$ km (b). ST2 balloons and IMS stations markers are coloured green, cyan, and red to indicate whether the detection is a balloon-like detection, a front-only detection, or if there no detection (see Section 4.1). $T_L(f = 0.1$ Hz, $r, z, z_{so} = 0.149$ km) altitude-range slices and associated ground (blue lines) and balloons' height (orange lines) smoothed transmission loss are shown for $\theta = 30^\circ$ (c), $\theta = 75^\circ$ (d) and $\theta = 295^\circ$ (e).

In the following we define the simulated pressure variance at sensor i by $P_{\text{sim}}^{(i)}(t) = \int_{f_{\text{min}}}^{f_{\text{max}}} \hat{p}_{\text{sim}}^{2(i)}(t, f) df$ where $\hat{p}_{\text{sim}}^{2(i)}(t, f)$ is the value of the spectrogram at f of the simulated pressure signal $p_{\text{sim}}^{(i)}(t)$. A comparison of the observed and the simulated waveforms at station *IS40* and the associated spectrograms is given in Supporting Information.

3 Overview of the 2021–2022 Hunga eruptive sequence reconstructed from balloon infrasound observations

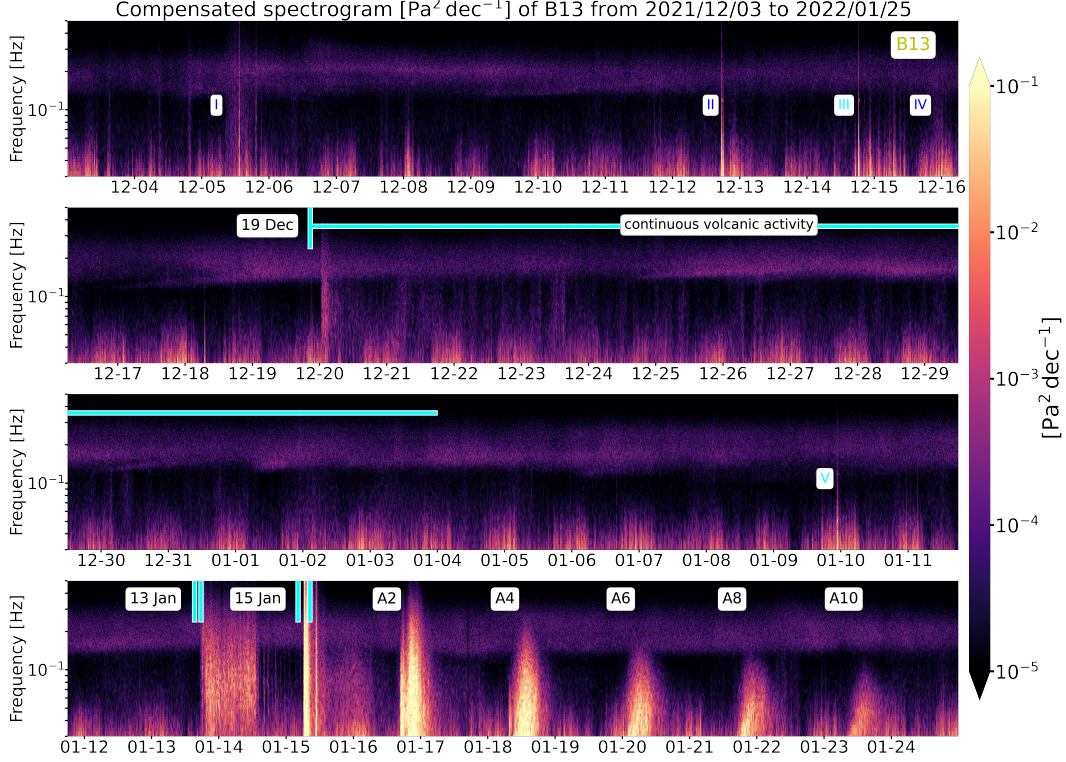


Figure 3. Compensated spectrogram [$\text{Pa}^2 \text{dec}^{-1}$] between 0.03 and 0.5 Hz of the corrected pressure recorded by *B13* from 3 December 2021 to 25 January 2022. Solid cyan lines indicate the dates of the main eruptive events of the 2021–2022 eruption sequence. Labels from I to V represent unidentified events whose colours depend on their presumed origin, light blue for artefacts related to flight physics and dark blue for an geophysical origin.

Two balloons, *B13* and *B15*, flew over the Pacific during the Hunga eruptive sequence. *B13*, in particular, remained within 6000 km of the volcano from 3 December 2021 to 25 January 2022 (Figure 1).

Figure 3 shows the compensated spectrogram ($\hat{p}_{\text{comp}}^{2(i)} = \hat{p}_{\text{obs}}^{2(i)}(t, f) \times f \times \log(10)$) in $\text{Pa}^2 \text{dec}^{-1}$ of its corrected pressure measurements.

They first reveal the persistent oceanic microbarom (Benioff & Gutenberg, 1939) between 0.12 and 0.2 Hz, at about $\sim 10^{-4} \text{Pa}^2 \text{dec}^{-1}$. Variations in magnitude and peak frequency occur over timescales of a few days, consistent with ground-based observations. They are attributed to shifts in the dominant oceanic source region and changes in meteorological conditions (Hupe et al., 2018). At frequencies below 0.05 Hz, a clear diurnal cycle is noted, with pressure variance peaking around local noon. While its cause remains uncertain, we hypothesize that it results from solar heating of the sensors and pay-

load rather than from a geophysical source. In contrast, the 0.05–0.1 Hz frequency band corresponds to a minimum in background energy, on the order of $\sim 10^{-7} \text{ Pa}^2 \text{ dec}^{-1}$. However, this state of quiescence is only interrupted by a few transient events (I to V in Figure 3), mostly of geophysical nature. This contrasts with spectrograms from pressure measurements at IMS stations, which often display elevated noise levels up to 10 Hz, frequently associated with periods of strong winds and daytime surface turbulence (see an example for station *IS40* in Figure B1).

Most transient events in the 0.05–0.12 Hz frequency range are consistent with the Hunga eruptive sequence, as described by Gupta et al. (2022) from satellite observations of the volcanic plume, and by Vergoz et al. (2022) and Donner et al. (2023) from IMS infrasound and seismic data. They are detailed below.

3.1 Initial eruption on 19 December 2021 and subsequent activity

After a 7-year period of dormancy, Hunga erupted on 19 December 2021. A 4.7 magnitude earthquake on 18 December 2021, at 16:49 UTC, at the location of the volcano and 100 km depth, was a likely precursor of the whole sequence. From an atmospheric perspective, the eruption began on 19 December 2021 at 20:46 UTC, origin time from the Reviewed Event Bulletin (REB), and was detected by 12 infrasound arrays (Vergoz et al., 2022), shortly after a 3.8-magnitude seismic event at 20:33 UTC. Geostationary satellite observations, sampled every 10 minutes, indicate that the volcanic plume began rising at approximately 20:40 UTC. It developed into an umbrella cloud, which expanded at an altitude of 15 ± 2 km to reach 100 km radius within 2 hours and remained visible for about 6 hours (Gupta et al., 2022).

The infrasound wavefront generated by this eruption was detected by balloon *B13* around 00:30 UTC (second line in Figure 3) on 20 December and clearly stands out as the largest-magnitude event since the beginning of the record on 3 December. Acoustic energy in the 0.08–0.12 Hz range (dominant frequency range) increased by more than one order of magnitude compared to background, reaching $\sim 10^{-2} \text{ Pa}^2 \text{ dec}^{-1}$. This level of activity persisted for about 3 hours in the records. Thereafter, enhanced levels of acoustic energy continued to be recorded onboard *B13* until January 4–5, with sporadic bursts of declining energy down to $\sim 5 \cdot 10^{-3} \text{ Pa}^2 \text{ dec}^{-1}$. This sustained, though intermittent, activity is consistent with ground infrasound measurements at IMS station *IS22* (Vergoz et al., 2022), and satellite observations of volcanic plumes up to 12 km (Gupta et al., 2022).

3.2 Major eruption on 13 January 2022

After a few days of relative rest, the acoustic energy measured onboard balloon *B13* rose again on 13 December around 18:00 UTC (fourth line in Figure 3) and remained relatively constant above $\sim 2 \cdot 10^{-2} \text{ Pa}^2 \text{ dec}^{-1}$ and up to $\sim 8 \cdot 10^{-2} \text{ Pa}^2 \text{ dec}^{-1}$ for a prolonged duration of about 20 hours before dropping back to background levels. A similar persisting rectangular pulse is observed by the other balloon in flight at the time, *B15*. Sustained activity was also detected by neighboring IMS stations, though with distinct pulses of enhanced emission recorded at 15:49 UTC (by 4 stations) and a larger pulse at 17:37 UTC (by 11 stations) in the REB (Vergoz et al., 2022). According to Gupta et al. (2022), the plume initially began to ascend around 15:20 UTC, approximately 30 minutes prior to the first infrasound REB event of the day, and formed an umbrella reaching 18 ± 2 km, which persisted for 22 hours as observed in infrared imagery. This lasting umbrella, longest in the sequence, is consistent with persistent high-energy in infrasound records, which may suggest prolonged emission associated with the feeding of the umbrella by the volcanic plume. The level of acoustic energy from *B13* drops back to background level around 13:30 UTC. Only 2–3 sporadic bursts of lower intensity are detected later on 14 January, mirroring a few small eruptive plumes in satellite observa-

tion (Gupta et al., 2022) and the decreasing activity seen in ground station (Vergoz et al., 2022).

On January 15, infrasound observations suggest a time of rest before the start of the climactic phase. On the contrary, both Gupta et al. (2022) and Van Eaton et al. (2023) mention plumes around 03:00 UTC based on geostationary observations, but this may result as a wrong identification of a natural cloud as a volcanic plume. We note that this cloud did not feature any lightning activity, contrary to the following plumes (Van Eaton et al., 2023).

3.3 Climactic eruption on 15 January 2022 and multiple revolutions of infrasound waves

We provide here only a brief summary of the climactic eruption of January 15 and subsequent multiple revolutions of the infrasound waves observed by *B13* (fourth line in Figure 3) following the description given in Podglajen et al. (2022), along with their relationship to plume evolution as reported in the literature. *B13* recorded 3 infrasound wave packets, which the authors identified as specific emission times during this eruption phase between 04:01 UTC and 08:30 UTC, namely:

- A major infrasound pulse, termed WP1 and backtracked to the volcano at 04:16 UTC, corresponding to the onset of the paroxysmal eruption determined by seismic and ground-base infrasound measurements (Poli & Shapiro, 2022; Matoza et al., 2022; Vergoz et al., 2022; Donner et al., 2023). Its emission coincides with the gradual ascent of the volcanic plume (Podglajen et al., 2022), which overshoot up to 58 km (Carr et al., 2022; Proud et al., 2022). In *B13* data, the corresponding burst of infrasound waves, arriving around 06:30 UTC, detectable up to 0.5 Hz, exhibits a maximum peak of $2 \times 10^2 \text{ Pa}^2 \text{ dec}^{-1}$ at 0.02–0.03 Hz.
- A secondary peak (WP2) arriving 07:05 UTC at 0.02–0.03 Hz and $1 \times 10^2 \text{ Pa}^2 \text{ dec}^{-1}$, backtraced at 07:53 UTC. Podglajen et al. (2022) noted that this double peak structure is also recorded at *IS22*. However, they were not able to relate it to volcanic plume overshoots seen in geostationary satellites. A seismic event recorded in the REB at 04:49 UTC (Donner et al., 2023) may correspond to this infrasound packet, though no definitive conclusion can be drawn.
- A later peak (WP3), reaching $\sim 40 \text{ Pa}^2 \text{ dec}^{-1}$, back-tracked to $\sim 08:30$ UTC, matching a later overshoot in geostationary plume observations in Carr et al. (2022).

At the ground, the infrasound and the Lamb waves generated by the eruption were thereafter observed to complete at most 8 revolutions around the Earth (Matoza et al., 2022; Vergoz et al., 2022). In balloons records, 5 revolutions are visible between 16 and 24 January (fourth line in Figure 3, see also Podglajen et al. (2022)). The series is limited only by the termination of the flights. After travelling a full circle, the acoustic energy of the wave packet decreases by a factor of 10 to 20, and could hence theoretically have been detected up to 7–8 times before reaching background levels. For successive passages (A2–A10), the convention of first antipodal arrivals, as defined by Matoza et al. (2022); Vergoz et al. (2022) is used in Figure 3.

3.4 Sporadic infrasound activity

Besides the Hunga sequence, other bursts of infrasound activity, marked from I to V in Figure 3, are monitored by *B13*. Two of these (III on 14 December around 19:00 UTC and V on 9 January around 23:00 UTC) are only detected by balloon *B13*, and might be artefacts related to flight physics. However, the 3 other bursts on 5 December around 12:00 UTC (I), 12 December around 18:00 UTC (II) and 15 December around 23:00 UTC (IV) are detected by several balloons and may correspond to other geophysical events

not necessarily linked to the eruptive sequence. Investigation of their origin is left for future studies.

Overall, balloon-borne infrasound records of the entire 2021-2022 Hunga eruptive sequence match ground-based infrasound and seismic observations presented in Matoza et al. (2022); Vergoz et al. (2022); Donner et al. (2023), and plume aerial activity in Gupta et al. (2022); Van Eaton et al. (2023). The few exceptions (e.g., the plume precursor around 3:00 UTC on January 15 in Gupta et al. (2022); Van Eaton et al. (2023)) may point to confusion between convective cloud and volcanic plumes in the interpretation of the satellite data. Ground-based infrasound records from a single station (see Figure B1) do not compare to the clean balloon records, which benefit from much lower and more stable background noise. The present analysis supports the conclusions of Podglajen et al. (2022), who, based solely on infrasound observations from the 15 January eruption, highlighted that the primary advantage of balloon-borne sensors lies in their low-noise environment and not on the potential larger signals in the elevated duct (Albert et al., 2023). However, specific array processing techniques significantly enhance its detection capabilities, and the Hunga sequence reconstructed from global IMS records in Vergoz et al. (2022) closely matches what is observed in balloon data.

To further assess the added value of balloon-borne measurements for volcanic monitoring relative to IMS observations, we focus next on the 19 December eruption, the initiation of the sequence, which is far more representative of typical volcanic activity than the 15 January event, an eruption unmatched since Krakatoa nearly 140 years earlier.

4 Focus on the 19 December 2021 eruption

The following discussion focuses on the eruption of 19 December 2021 at approximately 20:40 UTC, with a plume reaching 15 ± 2 km. This event is comparable to at least 10 eruptions over the 2015–2025 period, implying a recurrence interval of less than one year. The generated acoustic waves were typically around 10000 times smaller in magnitude than those from the 15 January event (see Section 3). This makes it an ideal case study for comparing stratospheric balloon-borne with ground-based stations infrasound measurements of typical eruptions.

4.1 Balloon-borne and IMS observations

All 5 ST2 balloons in flight detected infrasound from this eruption, as well as 9 IMS stations. The locations of the sensors at 20:40 UTC are shown in Figure 1, and a summary of their coordinates, altitude, distance to Hunga and back-azimuth is provided in Table 1, except for *IS36*, *IS45* and *IS57* which show no or unsatisfactory detections. As illustrated by monochromatic transmission loss maps for an acoustic source being the top of Hunga at 0.149 km (Figure 2), the various azimuths encompass strikingly different large-scale propagation conditions, with expected acoustic wave amplitudes varying by several orders of magnitude.

Pressure spectrograms observed at selected IMS stations (from 0.03 to 1 Hz) and ST2 balloons (0.03 to 0.5 Hz) following the eruption are shown in Figure 4 (records from other sensors can be found in Supporting Information). Volcanic infrasound are consistently detected across all ST2 balloons regardless of their altitude and position relative to Hunga. They appear as prolonged bursts of enhanced energy spanning the frequency range from 0.03 up to 0.5 Hz and a peak near 0.1 Hz. The first arrivals of the signals lie within theoretical window of arrivals (see Section 2.1.3) assuming for now an emission time at 20:40 UTC (Gupta et al., 2022).

For all balloons, enhanced energy levels (about $10^{-3} \text{ Pa}^2 \text{ dec}^{-1}$) persist for more than 3 hours, with a few 10 min-long more energetic bursts. Low energetic signals above

Table 1. Back-azimuth of the orthodrome from Hunga θ_{ortho} , detected back-azimuth θ_{PMCC} from PMCC, observed detection times of the wavefront t_{obs} , simulated wavefront celerities c_{sim} considering an acoustic source at 0.149 km, and detected horizontal phase speed c_{PMCC}^{ϕ} from PMCC.

Receiver	Condition	r [km]	z [km]	θ_{ortho}	θ_{PMCC}	t_{obs} (UTC)	c_{sim} [m s ⁻¹]	c_{PMCC}^{ϕ} [m s ⁻¹]
B8	upwind	4471	20.3	245.6°	-	20 01:11:40	271.0±0.4	-
B9	upwind	3542	20.3	223.1°	-	20 00:01:40	286.4±1.0	-
B12	upwind	2609	20.5	206.3°	-	19 23:00:50	290.8±1.6	-
B13	upwind	3870	20.5	235.6°	-	20 00:30:50	276.2±1.5	-
B15	downwind	3918	18.8	134.5°	-	20 00:07:30	306.5±0.5	-
IS04	downwind	6793	Ground	96.1°	92.4°	20 02:47:56	297.9±0.3	350
IS07	downwind	5233	Ground	99.9°	98.2°	20 01:26:00	304.1±0.4	353
IS22	downwind	1851	Ground	87.7°	90.6°	19 22:13:45	306.5±1.1	371
IS24	upwind	2759	Ground	259.3°	255.4°	19 23:33:55	258.8±2.0	359
IS40	downwind	3961	Ground	119.8°	119.9°	20 00:06:00	305.5±0.5	359
IS44	downwind	8563	Ground	154.2°	148.7°	20 04:43:40	-	338
IS55	upwind	6423	Ground	18.9°	11.6°	20 02:36:39	293.9±0.8	353
IS59	upwind	4923	Ground	206.6°	209.1°	20 01:14:21	-	360

0.08 Hz lasting for at least 10 hours after $t_{\text{obs}}^{(i)}$, consistent with the volcanic activity described in Section 3 is visible in balloon's records (see Supporting Information)

Contrary to the balloons, IMS arrays exhibit uneven detection of the eruption signal. Selected spectrograms in Figure 4 are stacked according to PMCC processing outputs to improve the SNR, yet the impact of noise and its variability across stations is striking, in contrast with balloon observations. While station *IS04* records a clear, isolated signal between 0.05 and 1 Hz around 04:00 UTC, lasting over 2 hours and resembling the balloon data in both shape (multiple peaks in time) and duration (referred as balloon-like detection in Figure 2), the energy pulse at *IS22* around 22:14 UTC is much shorter, less than 30 minutes according to PMCC, (referred as front-only detection in Figure 2) and difficult to distinguish from background noise without reference to PMCC output. At *IS24*, a persistent signal is detected, similar to those at the balloons and *IS04*, but rapidly followed by a wind-induced noise periods. Other stations fall into one of these two categories. Their geographic distribution does not directly align with large-scale propagation features (see Figure 2), the presence or absence of stratospheric ducts, but appears to be more influenced by time-varying wind-induced noise or local propagation effects.

To get a better sense of the temporal variability of the received acoustic signal, time series of energy integrated over the dominant frequency band $\Delta f_{\text{sig}} = [0.8, 0.12]$ Hz are shown in Figure 5. The time axis is offset to align the signals with respect to the first arrival of the detected wavefront (see Table 1). Energies vary by a factor of 2 to 3 across the balloons, with downwind balloon *B15* and crosswind balloon *B12* at the highest level (mean energy of $2 \cdot 10^{-4} \text{ Pa}^2$), and upwind balloons *B8*, *B9* and *B13* about half as high. Recordings feature a succession of wave packets, with 4 to 5 distinct local maxima separated by 30 minutes. For 4 balloons, the largest maximum is occurring about 1 hour and 20 minutes after the wavefront arrival. The energy peaks monitored by the balloons are quasi-synchronized in reduced time, with consistent shapes and durations, suggesting a common excitation sequence.

At ground level, the clarity of the signal detection remains station-dependent. Across all azimuths, some stations (*IS04*, *IS24*) exhibit long-lasting recordings (> 2 hours)

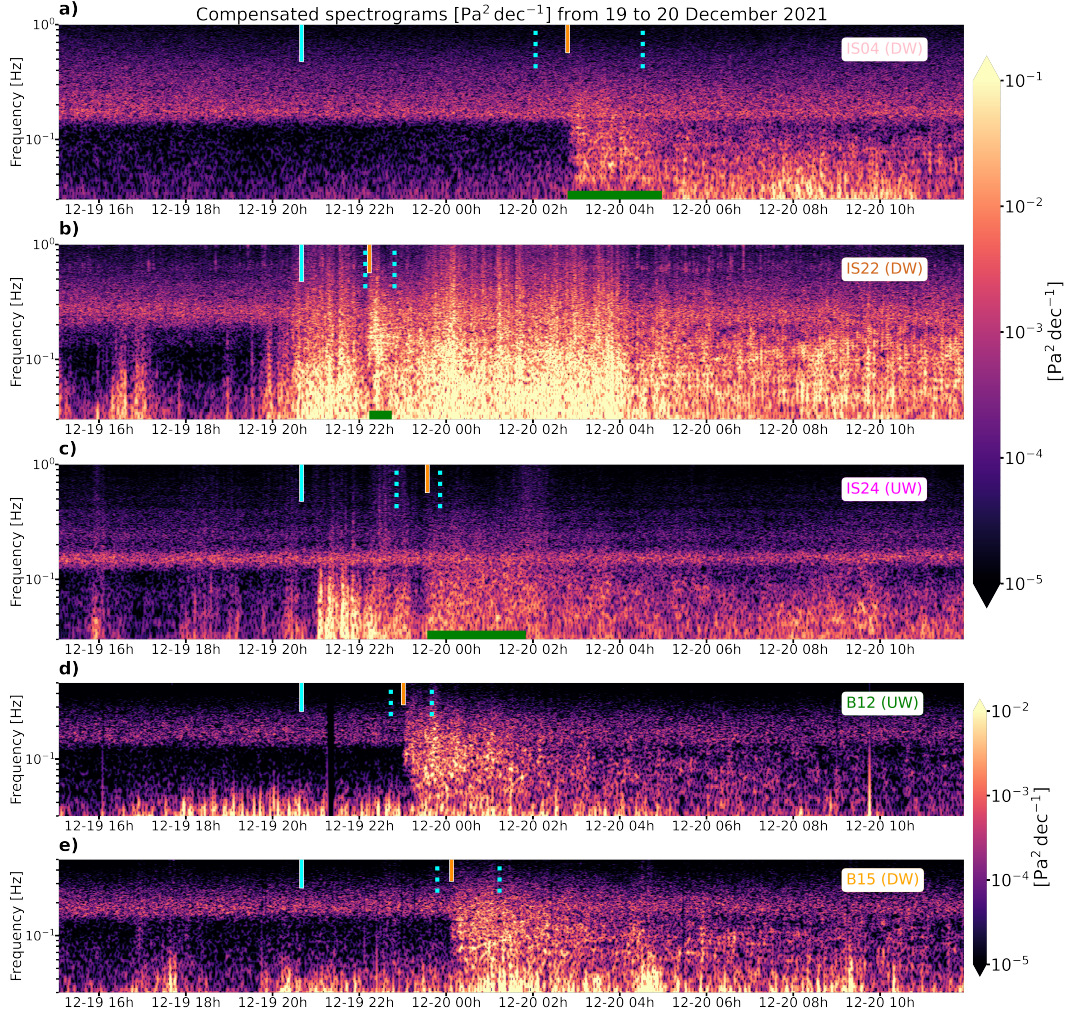


Figure 4. Compensated spectrograms [$\text{Pa}^2 \text{dec}^{-1}$] of the phase aligned pressure waveforms at IMS stations *IS04* (a), *IS22* (b), and *IS24* (c) (0.03–1 Hz), and of the corrected pressure recorded by ST2 balloons *B12* (d) and *B15* (e) (0.03–0.5 Hz), from 19 to 20 December 2021. Solid and dotted cyan lines indicate the eruption time and its theoretical arrivals at 240 and 350 m s^{-1} , respectively. Green rectangles denote PMCC detection periods associated with the event. Solid orange lines mark the observed detection times of the wavefront.

with several distinct peaks, similar to those observed on the balloons. In contrast, shorter detections (less than one hour) prevail at *IS22*, where only a single peak is identified by PMCC. The origin of this heterogeneity in detections is not always clear and likely reflects a combination of variable noise conditions and local propagation effects. This aspect will be discussed further in Section 5.1.

Following this period of intense acoustic energy, a persistent signal of lower energy continues for several hours with gradually decreasing levels. It is followed by several weeks of intermittent activity, as summarized in Section 3. The consistent structure of the signal across several receivers highlights a relationship with the chronology of the eruption.

4.2 Arrival times of infrasound waves and chronology of the 19 December eruption reconstructed from geostationary satellite observations

The onset of the eruptive sequence remains uncertain. Gupta et al. (2022) reports a start time of 20:40 UTC based on an infrared geostationary image acquired at 20:46 UTC, whereas the REB time is given as 20:46 UTC. Leveraging our unique combination of ground and upper-air observations, the chronology is revisited. The observed detection times at each sensor, $t_{\text{est}}^{(i)}$, can be back-projected to the location of Hunga knowing the infrasound celerity $c_{\text{sim}}^{(i)}$ estimated from the simulated waveforms (see Section 2.2.4) using:

$$t_{\text{est}}^{(i)} = t_{\text{obs}}^{(i)} - \frac{r^{(i)}}{c_{\text{sim}}^{(i)}} \quad (8)$$

Mean values of $c_{\text{sim}}^{(i)}$ for a 100 gravity wave realizations are provided in Table 1. While they are obtained for a source at the ground in the simulations, the results weakly depend on the source altitude (difference of about 1 minute). The anisotropy in $c_{\text{sim}}^{(i)}$ reflects the influence of distinct propagation paths and prevailing wind directions with slower propagation for upwind sensors ($\sim 280 \text{ m s}^{-1}$) and faster propagation for downwind sensors ($\sim 300 \text{ m s}^{-1}$). A possible explanation of this anisotropy can be that infrasound propagates more in the thermospheric duct and in the stratospheric duct for upwind and downwind sensors (see Figure 2 (c), (d) and (e)), respectively. Nippres and Green (2023) show that all the values of $c_{\text{sim}}^{(i)}$ found are not necessarily inconsistent with a propagation in the stratospheric duct only.

Using these values of $c_{\text{sim}}^{(i)}$ at sensor i , we estimate distributions of onset times for the event ranging from 20:27 UTC to 20:39 UTC, as shown in Figure 6. The average time, 20:33:59 UTC $\pm 202 \text{ s}$ is earlier than both the REB and geostationary analysis from Gupta et al. (2022). $\pm 202 \text{ s}$ uncertainty coupled with the detected signals shape analyses made in Section 4.1 is acceptable to confirm that all signals come from the same acoustic source. This calls for further investigations of the various records. Seismic data indicate a 3.8-magnitude earthquake at the location of Hunga at 20:33 UTC. Furthermore, a careful examination of geostationary observations in visible channels at improved 500 m resolution compared to the infrared channels in Gupta et al. (2022) reveals that the initial plume appears first on the 20:36 UTC image, consistent with the timing of the earthquake and infrasound.

The timing of the eruption is consistent across all balloon and stations and with records of seismic and plume aerial activities. However, the recordings of the eruption vary significantly across sensors, with some stations showing shorter or less structured sequences, in contrast to the multi-peak signals observed on the balloons (see Figure 5). The duration (see Figure 5) and evolution (see Figure 6) inferred from the balloon data are consistent with the plume development observed in satellite imagery (Gupta et al., 2022). In particular, satellite observations indicate a plume sustained for approximately

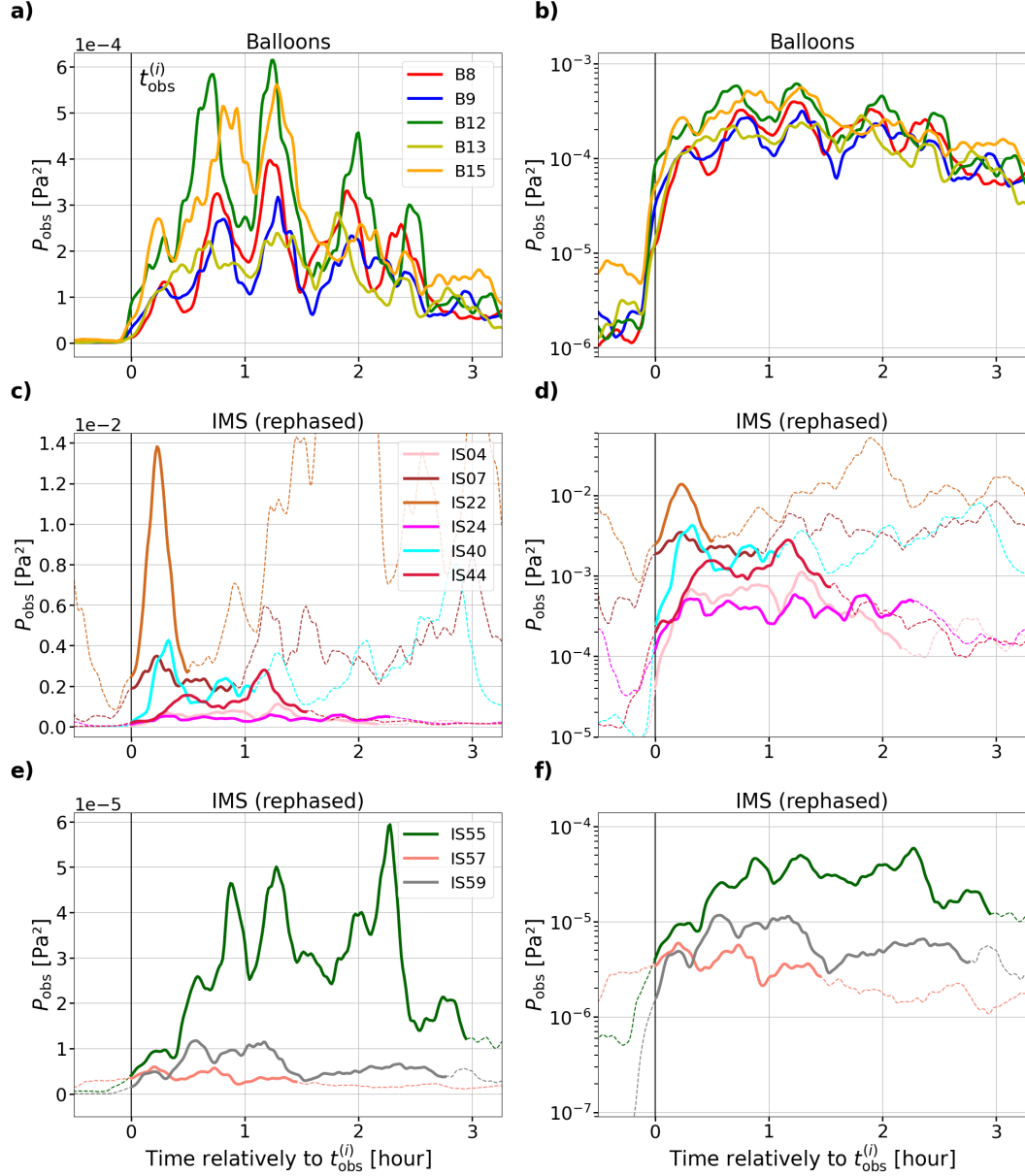


Figure 5. 5-minute smoothed time series of pressure variance $P_{\text{obs}}(t)$ on Δf_{sig} , around the detection window, for ST2 balloons (a, b) and IMS stations (c, d, e, f), shown with a linear (a, c, e) and a logarithmic scale (b, d, f). The time axis is shifted to align the first signal arrivals at $t_{\text{obs}}^{(i)}$. For IMS stations, the pressure variance is represented by dashed lines and bold solid lines within the PMCC detection windows.

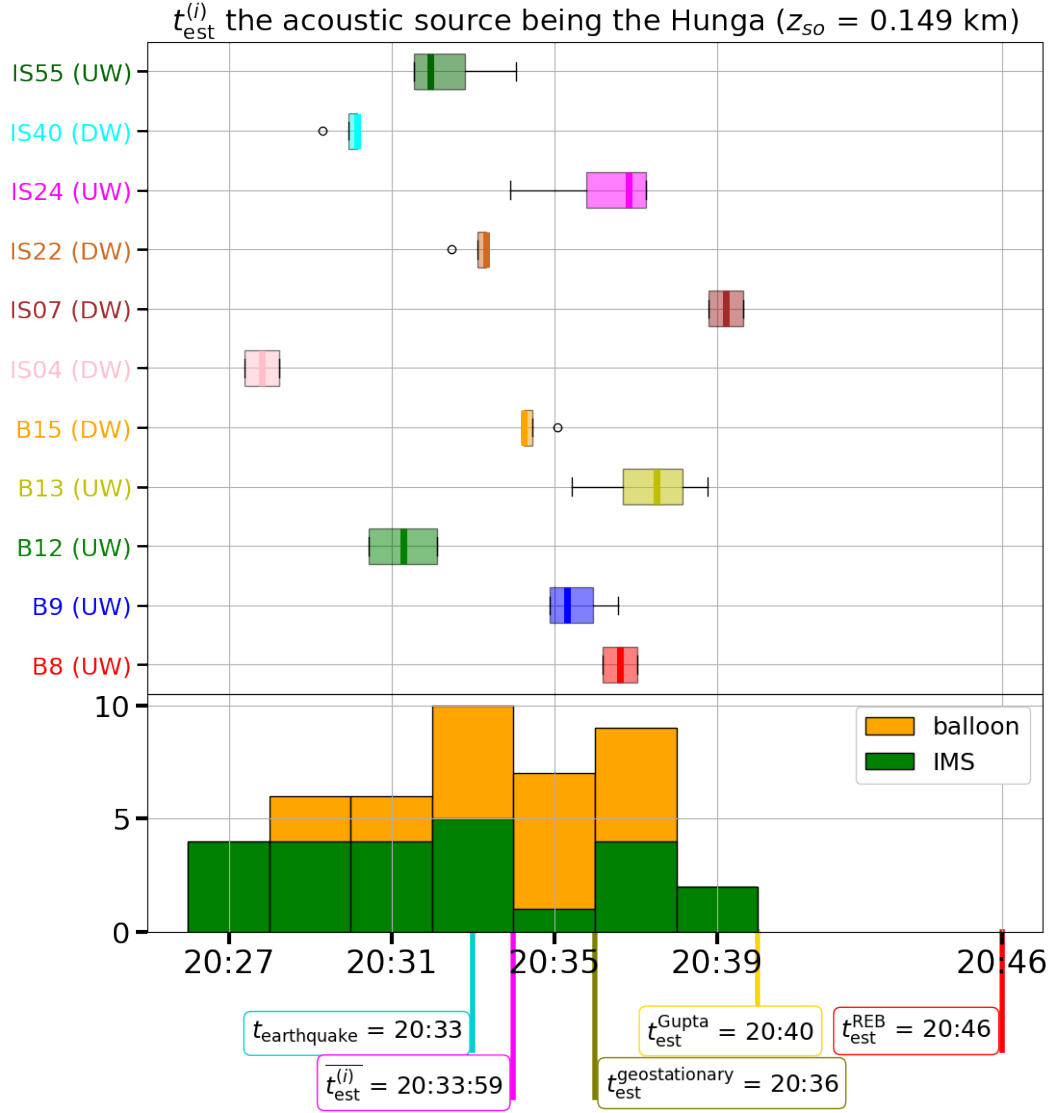


Figure 6. Distribution of the estimated time of the eruption $t_{\text{est}}^{(i)}$ computed from $t_{\text{obs}}^{(i)}$ and $c_{\text{sim}}^{(i)}$ at every considered sensors (upper panel). Histogram of $t_{\text{est}}^{(i)}$ with 2-minutes bins (lower panel). The distributions are obtained from simulation for a hundred different realisations of gravity waves. Time of the earthquake $t_{\text{earthquake}}$, mean of the estimated time of the eruption $t_{\text{est}}^{(i)}$, time of the first plume appearance on satellite imagery $t_{\text{est}}^{\text{geostationary}}$, time of the first plume appearance on satellite imagery $t_{\text{est}}^{\text{Gupta}}$ published by Gupta et al. (2022) and time of the eruption from REB bulletin $t_{\text{est}}^{\text{REB}}$ are marked by turquoise, magenta, light green, gold and red bold solid lines, respectively.

6 hours with multiple injection phases and a gradual decrease in altitude. The balloons, especially *B15*, recorded enhanced acoustic energy up to 10 hours after the onset of the event (see Supporting Information). While part of this signal may be attributed to the infrasonic coda, distinct bursts, in Figure 5 (a, b), 4 to 5 hours after the wavefronts' arrivals suggest ongoing eruptive activity.

Overall, the good agreement found between the balloon-borne signals and the plume evolution is consistent with the findings of Podglajen et al. (2022) for the 15 January case. Simulations with a ground-based source provide a reliable estimate of the celerity, allowing us to infer the eruption onset time at approximately 20:34 UTC.

4.3 Anisotropy of infrasound amplitudes in observations and simulations

Strong variability in infrasound attenuation between upwind and downwind sectors (Figure 2) is predicted at 0.1 Hz for a ground-based source, reaching several tens of dB. Although this anisotropy is reduced at balloon altitudes, the simulations still indicate a contrast of about 20 dB between *B13* and *B15*, which are located at comparable distances from Hunga but in upwind and downwind directions, respectively. In contrast, the observed difference in Figure 5 is more modest, remaining below an order of magnitude (< 10 dB).

In order to quantify the anisotropy in signal amplitude and its (in)consistency with the simulations, we compute $\overline{P_{\text{obs/sim}}^{(i)}}$, defined as the time-average of $P_{\text{obs/sim}}^{(i)}(t)$ at sensor i over a fixed-duration window starting at $t_{\text{obs/sim}}^{(i)}$. To account for temporal variability, $\overline{P_{\text{obs/sim}}^{(i)}}$ is evaluated over a range of window lengths from 10 minutes to 1 hour, in 5-minute increments. The attenuation in dB at sensor i , $T_{\text{obs/sim}}^{\text{B12},(i)}$, relative to the upwind reference balloon *B12*, is then computed from Equation 9:

$$T_{\text{obs/sim}}^{\text{B12},(i)} = 10 \log_{10} \left(\frac{\overline{P_{\text{obs/sim}}^{(i)}}}{\overline{P_{\text{obs/sim}}^{\text{B12}}}} \right) \quad (9)$$

Equation 9 gives that $T_{\text{obs/sim}}^{\text{B12},(i)} < 0 \Leftrightarrow \overline{P_{\text{obs/sim}}^{(i)}} < \overline{P_{\text{obs/sim}}^{\text{B12}}}$, $T_{\text{obs/sim}}^{\text{B12},(i)} > 0 \Leftrightarrow \overline{P_{\text{obs/sim}}^{(i)}} > \overline{P_{\text{obs/sim}}^{\text{B12}}}$ and $T_{\text{obs/sim}}^{\text{B12},(i)} = 0 \Leftrightarrow \overline{P_{\text{obs/sim}}^{(i)}} = \overline{P_{\text{obs/sim}}^{\text{B12}}}$. To quantify the overall agreement, we compute:

$$\bar{e}_r = \frac{1}{N_s} \sum_{i=1}^{N_s} \sqrt{\left(T_{\text{obs}}^{\text{B12},(i)} - T_{\text{sim}}^{\text{B12},(i)} \right)^2} \quad (10)$$

where $N_s = 10$ is the number of sensors, $\overline{T_{\text{obs}}^{\text{B12},(i)}}$ is the fixed-duration-windows-average of $T_{\text{obs}}^{\text{B12},(i)}$, $\overline{T_{\text{sim}}^{\text{B12},(i)}}$ is the fixed-duration-windows-average and the gravity-wave-realizations-average of $T_{\text{sim}}^{\text{B12},(i)}$.

We present distributions of $T_{\text{obs}}^{\text{B12},(i)}$ in Figure 7 (a). At every sensor, the variations of $\overline{T_{\text{obs}}^{\text{B12},(i)}}$ across fixed-duration windows is of typically 8 dB. Accounting for this uncertainty, the balloon observations appear nearly isotropic, regardless of the propagation conditions, and show magnitudes comparable to those at the upwind station *IS24*. In contrast, nearby downwind stations, particularly the closest one *IS22*, record the most energetic signals, exceeding those at *B12* by more than 10 dB.

The anisotropy of $T_{\text{sim}}^{\text{B12},(i)}$, obtained considering $z_{so} = 0.149$ km, also shown in Figure 7 (a), largely exceeds the observed anisotropy, both across balloons at the same altitude, and between ground and airborne sensors. For sensor i , good agreement (green background in Figure 7 (a)) between simulations and observations is attained when $T_{\text{obs}}^{\text{B12},(i)}$

lies between the maximum and the minimum of $T_{\text{sim}}^{B12(i)}$ with added gravity-wave perturbations (blue shaded area).

The simulations agree with the observations in that all upwind balloons receive similar signal levels. However, for downwind balloon *B15*, for all downwind IMS stations and for upwind stations *IS24* and *IS55*, the simulated amplitudes relative to *B12* are overestimated. Specifically,

- At balloon altitude, simulations predict at downwind balloon *B15* a larger amplitude of approximately +20 dB than that of the upwind reference *B12*, whereas observations indicate values of the same order of magnitude.
- At ground level, simulations predict at downwind stations *IS07*, *IS22*, and *IS40* a weaker attenuation relatively to the upwind reference *B12* of approximately +20 or +30 dB than at *IS24* where the observed differences is of about +10 or +15 dB.
- In the upwind sector, ground station *IS24* is simulated to be 15 dB above *B12*, while observations show only a few dB difference, and *IS55* is simulated to be 5 dB above *B12*, while observations show a difference of about ~ -10 dB
- Downwind ground stations are 20–30 dB higher than *B15* in the simulations, compared with 10–15 dB in the observations.

Overall, parabolic simulations with a ground-based source strongly overestimate the anisotropy of the propagation, with an error of 14.4 dB, with downwind ground amplitudes excessively enhanced relative to those at balloon level. This conclusion holds whether or not statistical gravity-wave perturbations are included in the calculations. Although gravity waves tend to reduce the anisotropy, their effect remains limited to about 8 dB, which was expected given that the signal considered is at low frequency (0.08 to 0.12 Hz) which are less affected by small-scaled fluctuations introduced following Gardner et al. (1993).

4.4 Evidence for an elevated acoustic source

We only considered acoustic waves emitted at the summit of the volcano ($z_{\text{so}} = 0.149$ km). However, satellite observations show that the plume rose up to an altitude of 15 ± 2 km and remained above 10 km for several hours (Gupta et al., 2022). Supersonic (Fee et al., 2013) and subsonic (Matoza et al., 2009; Matoza & Fee, 2014) volcanic plumes are a known source of infrasound. In order to quantify the sensitivity to this parameter, the altitude of the point source in simulations has been risen to $z_{\text{so}} = 5$ km, $z_{\text{so}} = 10$ km and $z_{\text{so}} = 15$ km. Where celerities are only weakly affected by these changes (see Section. 4.2), the anisotropy of the acoustic energy received across sensors is strongly affected, as shown in Figure 7 (b).

The anisotropy across sensors is gradually reduced when the source altitude is increased. Rising the source improves the agreement with the observations up to about 10 km. In particular, the overall realism of the simulation is improved, with an error of 9.7 dB, and they reasonably match the observations for all upwind balloons and the upwind station *IS24*. However, a mismatch of ~ 15 dB remains for downwind receivers. For a source altitude above 15 km, agreement is achieved for downwind sensors and remains satisfactory for upwind balloons. However, the signal at the upwind ground station *IS24* becomes overly attenuated and although the agreement is improved for upwind station *IS55*, a discrepancy of about 10 dB remains at this station.

This sensitivity test suggests that increasing the acoustic source altitude reduces the simulated anisotropy of signal’s amplitudes across sensors and brings the simulations closer to the observations. The altitude range yielding the best agreement (10–15 km) lies a few kilometres below the volcanic umbrella top, as estimated from geostationary satellite observations. This may suggests that infrasound emission from the plume is strongly

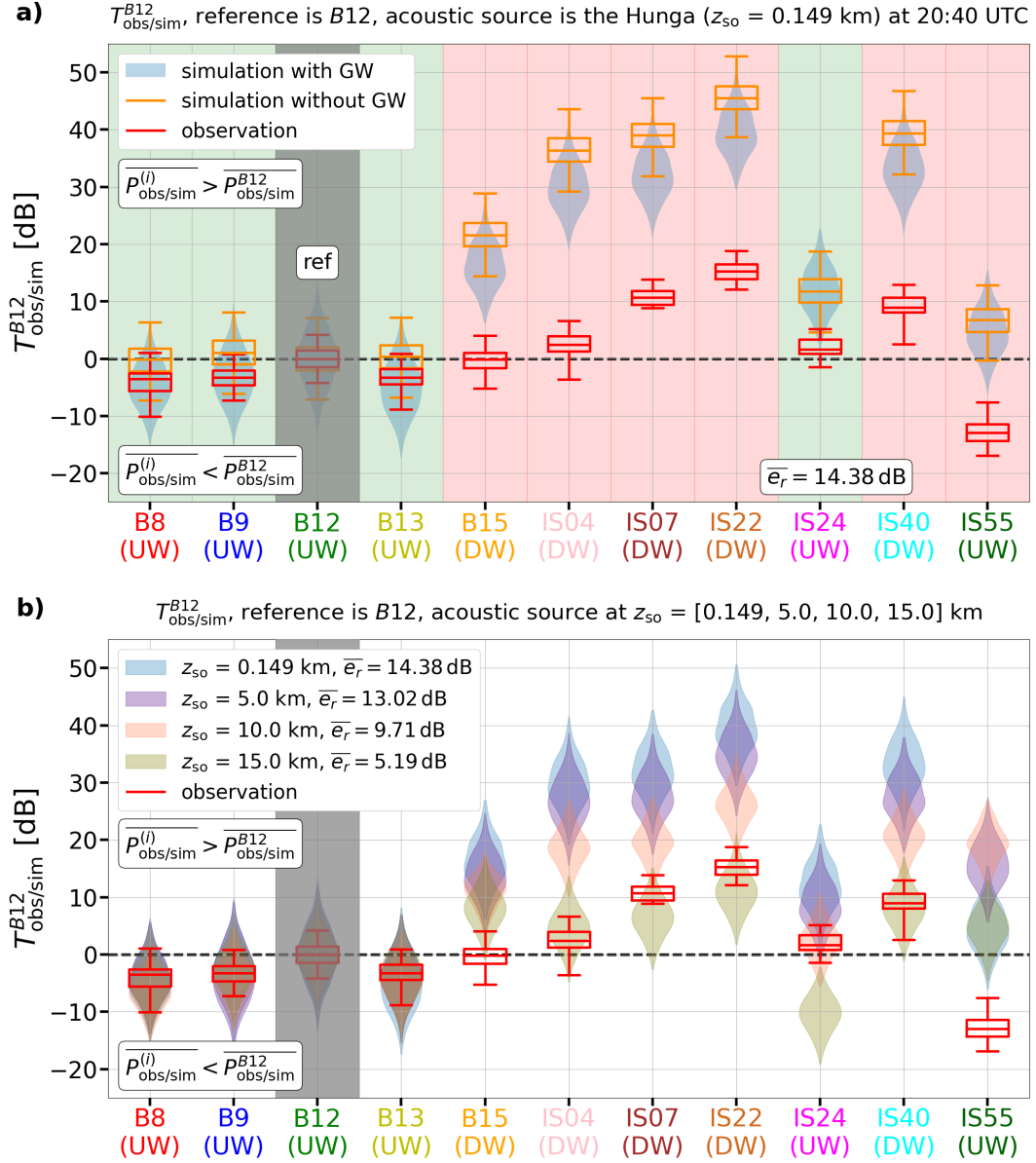


Figure 7. $T_{\text{obs/sim}}^{B12}$ attenuation relatively to *B12*. Observations are represented by red box-plots. On (a) simulations are obtained using atmospheric profiles with (blue shaded area) and without (orange boxplot) added gravity wave perturbations and the acoustic source is placed in simulations on 19 December 2021 at 20:40 UTC at $z_{\text{so}} = 0.149$ km. On (b) the acoustic source is placed in simulations using atmospheric profiles with added gravity wave perturbations on 19 December 2021 at 20:40 UTC at $z_{\text{so}} = 0.149$ km (blue), $z_{\text{so}} = 5.0$ km (purple), $z_{\text{so}} = 10.0$ km (orange) and $z_{\text{so}} = 15.0$ km (green).

enhanced near the umbrella altitude, compared with the atmospheric levels crossed by the jet below and near the vent. It is interesting to note that Zhang et al. (2025) also brings evidence for an elevated acoustic source based on fitting seismo-acoustic signals for the 15 January 2022 event.

Finally, it is interesting to note that, for later pulses beyond the first 3 hours of the eruption, the infrasound amplitude recorded by the upwind balloon *B15* is significantly enhanced (5–10 dB) relative to all downwind balloon sensors (see Supporting Information). According to the simulation results in Figure 7 (b), this pattern suggests a decrease in plume altitude, potentially to around 10 km. Such a subsidence is consistent with satellite observations. Although a detailed analysis is beyond the scope of this study, this example highlights the potential of continuous high-altitude measurements from multiple balloons for monitoring the temporal evolution of an eruption.

5 Discussion

5.1 Added value of balloon-borne to ground-based sensors infrasound sensors

In their analysis of the 15 January 2022 eruption, Podglajen et al. (2022) demonstrated the improved detection capability provided by balloon-borne measurements. However, given the exceptional energy of the Hunga eruption, which was detected by the entire IMS network, the added value of balloon measurements remains questionable for lower-energy explosive events.

The present analysis of the 19 December 2021 Hunga eruption nonetheless demonstrates the advantage of air-borne infrasound measurements for volcanic monitoring. While the balloons do not currently provide estimates of propagation direction and horizontal phase speed derived from PMCC processing of IMS arrays, they offer clean and continuous records in the 0.08–0.12 Hz band. This enables uninterrupted monitoring of the different phases of the event, providing insight into eruptive processes from vent activity to plume-level dynamics, with potential applications for volcanic hazard assessment.

The stability and reproducibility of the observed sequence across 5 balloons at different azimuths are clearly shown. This results from both the very low and stable background noise level around 0.1 Hz and the presence of a persistent high-altitude infrasound duct spanning a wide range of azimuths. In contrast, IMS stations are more strongly affected by the variability of wind-induced noise, as well as reduced signal amplitudes under less favourable propagation conditions, particularly upwind the stratospheric flow. Large-scale propagation conditions and noise are not the only factors affecting ground-based detections. For instance, *IS22*, the closest IMS station, benefits from favourable large-scale propagation conditions with a well-established stratospheric duct, yet it detects, according to PMCC, only a single peak over approximately 30 minutes, certainly because of a significant increase in wind level thereafter. This contrasts with the balloon observations, which show successive peaks of comparable magnitude over a period of approximately 3 hours.

5.2 Potential explanations of discrepancies between the observations and the simulations

In the previous section, parabolic simulations fail to reproduce exactly the observed distribution of amplitudes around the volcano. Several limitations associated with the approximations used in *ePape* may contribute to model–observation discrepancies and biases.

Long-range propagation paths are not strictly aligned with the great circle, however, the deviation between the PMCC-derived back-azimuth and the direction of Hunga

remains within a few degrees (Table 1). More importantly, the frequencies considered here (around 0.1 Hz) correspond to wavelengths of 3–4 km. The effective sound speed approximation assumes narrow-angle propagation, which is valid for the stratospheric duct in the downwind sector but becomes less reliable under upwind conditions. The validity of these simulations also becomes more questionable for long-range propagation in a complex and uncertain three-dimensional atmospheric medium. However, it is unlikely that intrinsic limitations of the parabolic-equation modelling alone can explain the observed bias.

Another possible source of error lies in the characteristics of the acoustic source itself. The emitted signal certainly deviate from the ideal assumptions adopted in this theoretical study. Full agreement is not achieved in our point-source framework which is not unexpected given that variations in source directivity, position, and temporal fluctuations can all introduce discrepancies between the simulated and measured acoustic signals.

A possible source of the discrepancies between observations and simulations can be found in the construction of the atmospheric profiles used for these simulations. Kristoffersen et al. (2026) has demonstrated that important differences between atmospheric models exist by showing that in the equatorial stratosphere significant discrepancies are found between ERA5 and the ICOsahedral Nonhydrostatic model (ICON) (Zängl et al., 2015) when representing the stratospheric semi-annual oscillation (SAO) of zonal wind ($\sim 10^\circ\text{N}$ – $\sim 10^\circ\text{S}$). Comparisons of the results presented in Section 4 with those obtained from simulations based on atmospheric profiles derived from the Whole Atmosphere Community Climate Model (WACCM) (Gettelman et al., 2019) (not presented) showed that, overall, the conclusions reached here still hold when another atmospheric model is used. However, improvements in atmospheric modelling, coupled with a more realistic and specific model of unresolved gravity waves, certainly could improve the match between the observations and the simulations.

6 Conclusion

This study provides an assessment of balloon-borne infrasound measurements for monitoring a complete volcanic eruptive sequence with moderate intensity eruptions. Using the unique measurements from balloons of the ST2 campaign, which flew in the vicinity of Hunga during the entire December 2021–January 2022 eruptive sequence, we draw the following principal conclusions.

First, balloon-borne pressure sensors provide a remarkably faithful reconstruction of the eruptive chronology. The excellent agreement between the infrasound records from balloons, the IMS ground network, and independent satellite and seismic observations confirms that stratospheric balloons are a reliable platform for volcano monitoring making free-flying acoustic arrays a valuable complement to ground-based infrasound monitoring networks. In the case of the initial eruption on 19 December 2021 balloons even helped refine the eruption onset time, estimated at 20:34 UTC earlier than previous estimations, and monitored long-duration signals consistent with a sustained umbrella cloud. The clean records enabled the identification of a complex sequence of pulses offering a perspective on temporal source variability not accessible from individual ground stations.

Second, we demonstrate the substantial added value of balloon-borne sensors over traditional ground-based arrays for common eruptive events. Unlike the cataclysmic eruption on 15 January 2022, where generated signal dominated everything else, the eruption on 19 December 2021 was of more common power with a recurrence interval of less than one year, with acoustic energies roughly 10000 times smaller. All 5 in-flight balloons clearly detected the eruption, with remarkably consistent signals across different azimuths and propagation conditions primarily thanks to very low wind and turbulence-induced acoustic noise. In contrast, the IMS ground-based network, strongly affected by local wind

conditions, showed highly uneven detections with some stations recording balloon-like signals and other partial or no signal from Hunga. Our results thus extend the conclusions of Podglajen et al. (2022) from a once-in-a-century event to the class of moderate eruptions that occur around one time per year.

Third, by combining observations with parabolic-equation based wave propagation simulations, we provide new evidence for the role of the volcanic umbrella cloud as an infrasound source. Simulations using a source at Hunga’s level drastically overestimated the acoustic anisotropy of the attenuation between upwind and downwind directions. Placing the source at altitudes of 10–15 km, within the observed umbrella cloud, significantly reduced this bias and brought the simulations into much closer agreement with observations. The temporal evolution of amplitudes may even hints at a gradual descent of the source altitude over several hours, consistent with the observed plume subsidence.

Current ground-based networks, such as the IMS, remain indispensable for their array-processing capabilities that provide source direction and phase velocity. However, their vulnerability to wind-induced acoustic noise and boundary layer variability limits their effectiveness for systematic detection of moderate eruptions and explosive events, particularly in regions lacking dense station coverage. This study shows that a small array of long-duration stratospheric balloons offers a significant advantage in explosive events monitoring, providing consistent and high-quality observations, establishing it as a complementary tool suited to fill this gap.

The upcoming balloon’s launch of ST2 campaign, scheduled for October 2026, will extend these measurements with an improved payload and longer-duration flights, offering the opportunity to apply the methods developed here to other explosive events, potentially capturing moderate volcanic eruptions or other explosive events, and thereby further establish balloon-borne infrasound as a routine tool for geophysical monitoring.

Appendix A Construction of atmospheric profiles for simulations’ inputs

The grid chosen for constructing atmospheric profiles for simulation inputs has been set to one vertical profile every 100 km with a vertical resolution of 1 km. The longitude, latitude, and back-azimuth at 100 km intervals along a great circle on the Earth’s surface are computed taking into account the Earth’s curvature. Atmospheric field (see Section 2.2.2) are linearly interpolated in latitude, longitude and time at each point of the grid. Horizontal winds is projected onto the propagation direction with respect to the azimuth at every point on the great circle. In the framework of the effective sound speed approximation (see Section 2.2.1), the vertical wind is disregarded. As the propagation is primarily over the ocean, topography is disregarded.

Appendix B Overview of the 2021–2022 Hunga eruptive sequence reconstructed from balloon infrasound observations

Conflict of Interest Disclosure

The authors declare there are no conflicts of interest for this manuscript.

Acknowledgments

All authors gratefully acknowledge the financial support of l’Agence de l’Innovation de Défense (AID) and Indo-French Centre for the Promotion of Advanced Research (IFC-PAR). The sponsorship of CNES, CNRS-INSU and NSF to Strateole-2 balloon activities is gratefully acknowledged. The authors thank the CTBTO and the IMS station operators for guaranteeing the high quality of the infrasound data and acknowledge the CTBTO

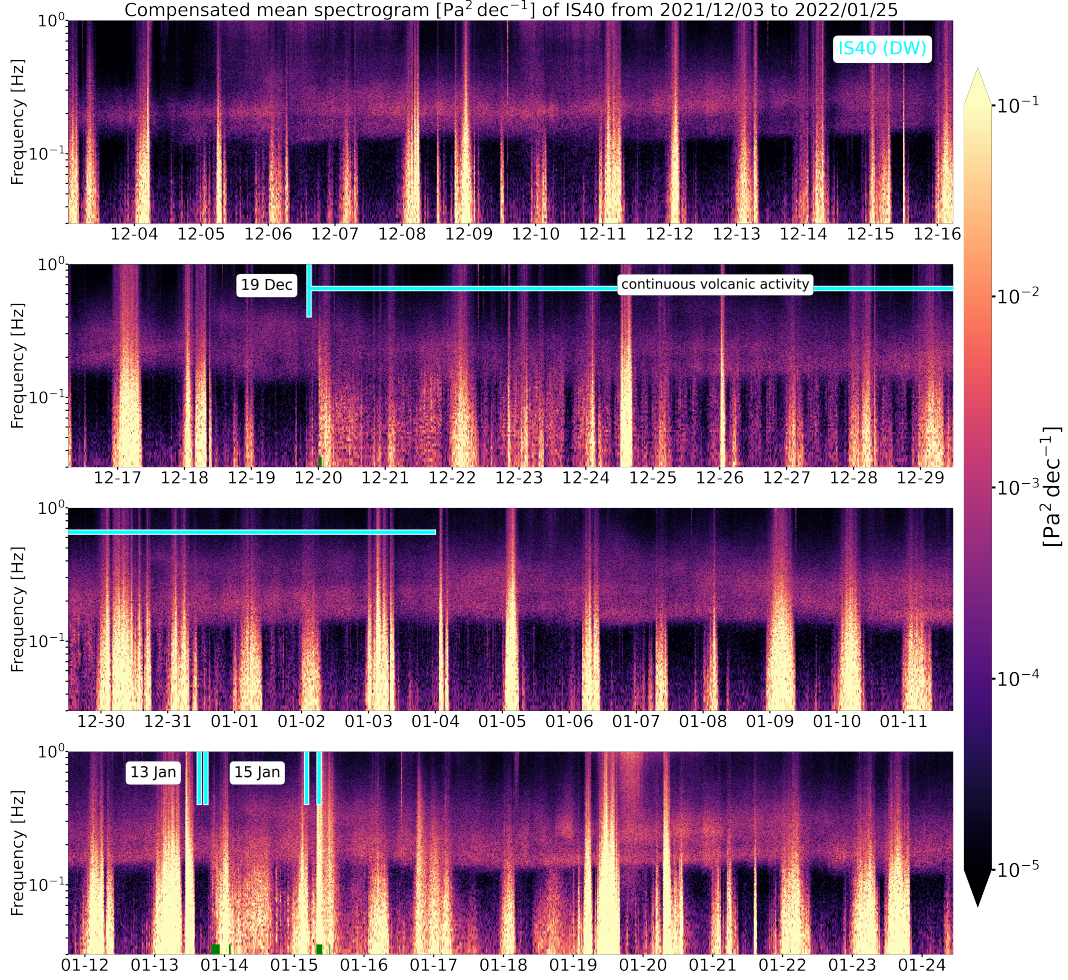


Figure B1. Compensated mean spectrogram [$\text{Pa}^2 \text{dec}^{-1}$] between 0.03 and 1 Hz of the phase aligned pressure waveforms at IMS stations *IS40* from 3 December 2021 to 25 January 2022. Solid cyan lines indicate the dates of the main eruptive events of the 2021–2022 eruption sequence. Green rectangles correspond to PMCC’s detection periods of signal from Hunga.

Preparatory Commission for providing limited access (via vDEC) to the IMS infrasound network data. The authors thank Robin Matoza, Christophe Millet, Julien Vergoz and Samuel Kristoffersen for insightful discussions.

Data Availability Statement

Strateole-2 data (*Stratéole-2 C1 campaign dataset*, 2021) are available at <https://strateole2.aeris-data.fr/catalogue/>. IMS data are available on request from the CTBTO Preparatory Commission for scientific purposes through the virtual Data Exploitation Centre (vDEC) at <https://www.ctbto.org/specials/vdec/>. ERA5 data are available at <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-complete?tab=overview> (Hersbach et al., 2023). HWM14 (Ilma, 2017) and NRLMSIS (Lucas, 2025) data are available through python packages available at <https://github.com/gemini3d/hwm14> and <https://github.com/SWxTREC/pymysis>, respectively. *NC-PAprop* can be downloaded through Waxler et al. (2021b).

Author Contributions

P. H.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. A. P.: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – original draft. A. LP.: Conceptualization, Methodology, Supervision, Writing – review & editing. C. L.: Investigation, Writing – review & editing. A. H.: Data curation, Writing – review & editing. S. BG.: Methodology, Writing – review & editing. M. F.: Methodology, Writing – review & editing. Q. B.: Methodology, Writing – review & editing. L. S.: Formal analysis, Investigation. SV. P.: Writing – review & editing.

References

- Albert, S. A., Bowman, D. C., Silber, E. A., & Dannemann Dugick, F. K. (2023). The atmosofar channel: First direct observations of an elevated acoustic duct. *Earth and Space Science*, 10(10), e2023EA003149. (e2023EA003149 2023EA003149) doi: <https://doi.org/10.1029/2023EA003149>
- Alcoverro, B., & Le Pichon, A. (2005). Design and optimization of a noise reduction system for infrasonic measurements using elements with low acoustic impedance. *The Journal of the Acoustical Society of America*, 117(4), 1717–1727. doi: 10.1121/1.1804966
- Banister, J. R., & Hereford, W. V. (1991). Observed high-altitude pressure waves from an underground and a surface explosion. *Journal of Geophysical Research: Atmospheres*, 96(D3), 5185–5193. doi: <https://doi.org/10.1029/90JD02640>
- Bass, H. E., Hetzer, C. H., & Raspet, R. (2007). On the speed of sound in the atmosphere as a function of altitude and frequency. *Journal of Geophysical Research: Atmospheres*, 112(D15). doi: <https://doi.org/10.1029/2006JD007806>
- Benioff, H., & Gutenberg, B. (1939). Waves and currents recorded by electromagnetic barographs. *Bulletin of the American Meteorological Society*, 20(10), 421–428.
- Bowman, D., Lees, J., Cutts, J., Komjathy, A., Young, E., Seiffert, K., ... Arrow-smith, S. (2019). Geoacoustic observations on drifting balloon-borne sensors. In A. Le Pichon, E. Blanc, & A. Hauchecorne (Eds.), *Infrasound monitoring for atmospheric studies: Challenges in middle atmosphere dynamics and societal benefits* (pp. 125–171). Cham: Springer International Publishing. doi: 10.1007/978-3-319-75140-5_4
- Bowman, D. C., & Krishnamoorthy, S. (2021). Infrasound from a buried chemical explosion recorded on a balloon in the lower stratosphere. *Geophysical Research Letters*, 48(21), e2021GL094861. (e2021GL094861 2021GL094861) doi: <https://doi.org/10.1029/2021GL094861>

- Brachet, N., Brown, D., Le Bras, R., Cansi, Y., Mialle, P., & Coyne, J. (2009). Monitoring the earth's atmosphere with the global ims infrasound network. In A. Le Pichon, E. Blanc, & A. Hauchecorne (Eds.), *Infrasound monitoring for atmospheric studies* (pp. 77–118). Dordrecht: Springer Netherlands. doi: 10.1007/978-1-4020-9508-5_3
- Brissaud, Q., Kong, C., Wilding, J. D., Gülcher, A., Jackson, J. M., Froment, M., ... van Zelst, I. (2025). Aerial and space-borne seismology on venus: Viability and design implications for future missions.
- Brissaud, Q., Krishnamoorthy, S., Jackson, J. M., Bowman, D. C., Komjathy, A., Cutts, J. A., ... Walsh, G. J. (2021). The first detection of an earthquake from a balloon using its acoustic signature. *Geophysical Research Letters*, 48(12), e2021GL093013. (e2021GL093013 2021GL093013) doi: https://doi.org/10.1029/2021GL093013
- Cameijo, A. J., Le Pichon, A., Sklab, Y., Arib, S., Brissaud, Q., Näsholm, S. P., ... Aknine, S. (2025). Toward real-time assessment of infrasound event detection capability using deep learning-based transmission loss estimation. *Journal of Geophysical Research: Atmospheres*, 130(19), e2025JD043577. (e2025JD043577 2025JD043577) doi: https://doi.org/10.1029/2025JD043577
- Cansi, Y. (1995). An automatic seismic event processing for detection and location: The p.m.c.c. method. *Geophysical Research Letters*, 22(9), 1021-1024. doi: https://doi.org/10.1029/95GL00468
- Cansi, Y., & Pichon, A. L. (2008). Infrasound event detection using the progressive multi-channel correlation algorithm. In D. Havelock, S. Kuwano, & M. Vorländer (Eds.), *Handbook of signal processing in acoustics* (pp. 1425–1435). New York, NY: Springer New York. doi: 10.1007/978-0-387-30441-0_77
- Carr, J. L., Horvath, A., Wu, D. L., & Friberg, M. D. (2022). Stereo plume height and motion retrievals for the record-setting hunga tonga-hunga ha'apai eruption of 15 january 2022. *Geophysical Research Letters*, 49(9), e2022GL098131. (e2022GL098131 2022GL098131) doi: https://doi.org/10.1029/2022GL098131
- Coffman, J. W. (1965). A balloon-borne microphone system. , 281.
- Copernicus Climate Change Service. (2020). *ERA5: compute pressure and geopotential on model levels, geopotential height and geometric height*. Retrieved from https://confluence.ecmwf.int/display/CKB/ERA5\%3A+compute+pressure+and+geopotential+on+model+levels\%2C+geopotential+height+and+geometric+height (Copernicus Knowledge Base - ECMWF Confluence Wiki)
- Donner, S., Steinberg, A., Lehr, J., Pilger, C., Hupe, P., Gaebler, P., ... Ceranna, L. (2023). The january 2022 hunga volcano explosive eruption from the multi-technological perspective of ctbt monitoring. *Geophysical Journal International*, 235(1), 48-73. doi: 10.1093/gji/ggad204
- Drob, D. P., Emmert, J. T., Meriwether, J. W., Makela, J. J., Doornbos, E., Conde, M., ... Klenzing, J. H. (2015). An update to the horizontal wind model (hwm): The quiet time thermosphere. *Earth and Space Science*, 2(7), 301-319. doi: https://doi.org/10.1002/2014EA000089
- Duchamp, C., Legras, B., Podglajen, A., Sellitto, P., Bourassa, A. E., Rozanov, A., ... Zawada, D. J. (2025). Aerosol composition and extinction of the 2022 hunga plume using caliop. *EGUsphere*, 2025, 1–24. doi: 10.5194/egusphere-2025-3355
- Fee, D., Matoza, R. S., Gee, K. L., Neilsen, T. B., & Ogden, D. E. (2013). Infrasonic crackle and supersonic jet noise from the eruption of nabro volcano, eritrea. *Geophysical Research Letters*, 40(16), 4199-4203. doi: https://doi.org/10.1002/grl.50827
- Froment, M., Brissaud, Q., Näsholm, S. P., & Schweitzer, J. (2025). Balloon seismology enables subsurface inversion without ground stations. *Communications Earth & Environment*, 6(1), 949. doi: 10.1038/s43247-025-02917-7
- Garcia, R. F., Klotz, A., Hertzog, A., Martin, R., G  rier, S., Kassarian, E., ...

- Mimoun, D. (2022). Infrasound from large earthquakes recorded on a network of balloons in the stratosphere. *Geophysical Research Letters*, 49(15), e2022GL098844. (e2022GL098844 2022GL098844) doi: <https://doi.org/10.1029/2022GL098844>
- Garcia, R. F., van Zelst, I., Kawamura, T., Näsholm, S. P., Horleston, A., Klaasen, S., ... De Toffoli, B. (2024). Seismic wave detectability on venus using ground deformation sensors, infrasound sensors on balloons and airglow imagers. *Earth and Space Science*, 11(11), e2024EA003670. (e2024EA003670 2024EA003670) doi: <https://doi.org/10.1029/2024EA003670>
- Gardner, C. S., Hostetler, C. A., & Franke, S. J. (1993). Gravity wave models for the horizontal wave number spectra of atmospheric velocity and density fluctuations. *Journal of Geophysical Research: Atmospheres*, 98(D1), 1035-1049. doi: <https://doi.org/10.1029/92JD02051>
- Gottelman, A., Mills, M. J., Kinnison, D. E., Garcia, R. R., Smith, A. K., Marsh, D. R., ... Randel, W. J. (2019). The whole atmosphere community climate model version 6 (waccm6). *Journal of Geophysical Research: Atmospheres*, 124(23), 12380-12403. doi: <https://doi.org/10.1029/2019JD030943>
- Godin, O. A. (2002). An effective quiescent medium for sound propagating through an inhomogeneous, moving fluid. *The Journal of the Acoustical Society of America*, 112(4), 1269-1275. doi: 10.1121/1.1504853
- Gupta, A. K., Bennartz, R., Fauria, K. E., & Mittal, T. (2022). Eruption chronology of the december 2021 to january 2022 hunga tonga-hunga ha'apai eruption sequence. *Communications Earth & Environment*, 3(1), 314. doi: 10.1038/s43247-022-00606-3
- Hedlin, M. A. H., & Drob, D. P. (2014). Statistical characterization of atmospheric gravity waves by seismoacoustic observations. *Journal of Geophysical Research: Atmospheres*, 119(9), 5345-5363. doi: <https://doi.org/10.1002/2013JD021304>
- Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., ... Thépaut, J.-N. (2023). *Era5 hourly data on single levels from 1940 to present*. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Retrieved from <https://doi.org/10.24381/cds.adbb2d47> doi: 10.24381/cds.adbb2d47
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horanyi, A., Muñoz-Sabater, J., ... Thépaut, J.-N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999-2049. doi: <https://doi.org/10.1002/qj.3803>
- Hertzog, A., Cocquerez, P., Guilbon, R., Valdivia, J.-N., Venel, S., Basdevant, C., ... Éric Schmitt (2007). Stratéole/vorcore—long-duration, superpressure balloons to study the antarctic lower stratosphere during the 2005 winter. *Journal of Atmospheric and Oceanic Technology*, 24(12), 2048 - 2061. doi: 10.1175/2007JTECHA948.1
- Hertzog, A., & Plougonven, R. (2021). Strateole-2: High-resolution observations of the tropical tropopause layer with long-duration balloons. In *Egu general assembly conference abstracts* (pp. EGU21-7109).
- Hupe, P., Ceranna, L., Pilger, C., de Carlo, M., Le Pichon, A., Kaifler, B., & Rapp, M. (2018). Assessing middle atmosphere weather models using infrasound detections from microbaroms. *Geophysical Journal International*, 216(3), 1761-1767. doi: 10.1093/gji/ggy520
- Ilma, R. (2017, January). *rilma/pyhwm14: Official release of the hwm14wrapper in python*. Zenodo. Retrieved from <https://doi.org/10.5281/zenodo.240890> doi: 10.5281/zenodo.240890
- Johnson, J. B., & Ripepe, M. (2011). Volcano infrasound: A review. *Journal of Volcanology and Geothermal Research*, 206(3), 61-69. doi: <https://doi.org/10.1016/j.jvolgeores.2011.06.006>
- Kloss, C., Berthet, G., Sellitto, P., Bartolome Garcia, I., Briaud, E., Das, R. C., ...

- Hegglin, M. I. (2025). Cross-hemispheric transport of the hunga aerosol plume: In situ evidence and radiative effects from the northern hemisphere. *EGU sphere*, 2025, 1–24. doi: 10.5194/egusphere-2025-2091
- Kristoffersen, S., Listowski, C., Wing, R., Khaykin, S., Baumgarten, G., Hauchecorne, A., . . . Vergoz, J. (2026). Atmospheric specifications for infrasound studies: 1. operational analyses. *Journal of Geophysical Research: Atmospheres*, 131(1), e2025JD044921. (e2025JD044921 2025JD044921) doi: <https://doi.org/10.1029/2025JD044921>
- Listowski, C., Stephan, C. C., Le Pichon, A., Hauchecorne, A., Kim, Y.-H., Achatz, U., & Bölöni, G. (2025). Stratospheric gravity waves impact on infrasound transmission losses across the international monitoring system. *Pure and Applied Geophysics*, 182(12), 5015–5047. doi: 10.1007/s00024-024-03467-3
- Lucas, G. (2025, July). *pymysis*. Zenodo. doi: 10.5281/zenodo.5348502
- Marty, J. (2019). The ims infrasound network: Current status and technological developments. In A. Le Pichon, E. Blanc, & A. Hauchecorne (Eds.), *Infrasound monitoring for atmospheric studies: Challenges in middle atmosphere dynamics and societal benefits* (pp. 3–62). Cham: Springer International Publishing. doi: 10.1007/978-3-319-75140-5_1
- Massman, W. J. (1978). On the nature of vertical oscillations of constant volume balloons. *Journal of Applied Meteorology and Climatology*, 17(9), 1351 - 1356. doi: 10.1175/1520-0450(1978)017<1351:OTNOVO>2.0.CO;2
- Matoza, R. S., & Fee, D. (2014). Infrasonic component of volcano-seismic eruption tremor. *Geophysical Research Letters*, 41(6), 1964–1970. doi: <https://doi.org/10.1002/2014GL059301>
- Matoza, R. S., Fee, D., Assink, J. D., Iezzi, A. M., Green, D. N., Kim, K., . . . Wilson, D. C. (2022). Atmospheric waves and global seismoacoustic observations of the january 2022 hunga eruption, tonga. *Science*, 377(6601), 95–100. doi: 10.1126/science.abo7063
- Matoza, R. S., Fee, D., Garcés, M. A., Seiner, J. M., Ramón, P. A., & Hedlin, M. A. H. (2009). Infrasonic jet noise from volcanic eruptions. *Geophysical Research Letters*, 36(8). doi: <https://doi.org/10.1029/2008GL036486>
- Nippres, A., & Green, D. N. (2023). Global empirical models for infrasonic celerity and backazimuth. *Geophysical Journal International*, 235(2), 1912–1925. doi: 10.1093/gji/ggad334
- Picone, J. M., Hedin, A. E., Drob, D. P., & Aikin, A. C. (2002). Nrlmsise-00 empirical model of the atmosphere: Statistical comparisons and scientific issues. *Journal of Geophysical Research: Space Physics*, 107(A12), SIA 15-1-SIA 15-16. doi: <https://doi.org/10.1029/2002JA009430>
- Podglajen, A., Hertzog, A., Plougonven, R., & Legras, B. (2016). Lagrangian temperature and vertical velocity fluctuations due to gravity waves in the lower stratosphere. *Geophysical Research Letters*, 43(7), 3543–3553. doi: <https://doi.org/10.1002/2016GL068148>
- Podglajen, A., Le Pichon, A., Garcia, R. F., G  rier, S., Millet, C., Bedka, K., . . . Hertzog, A. (2022). Stratospheric balloon observations of infrasound waves from the 15 january 2022 hunga eruption, tonga. *Geophysical Research Letters*, 49(19), e2022GL100833. (e2022GL100833 2022GL100833) doi: <https://doi.org/10.1029/2022GL100833>
- Poli, P., & Shapiro, N. M. (2022). Rapid characterization of large volcanic eruptions: Measuring the impulse of the hunga tonga ha’apai explosion from teleseismic waves. *Geophysical Research Letters*, 49(8), e2022GL098123. (e2022GL098123 2022GL098123) doi: <https://doi.org/10.1029/2022GL098123>
- Poste, B., Charbit, M., Le Pichon, A., Listowski, C., Roueff, F., & Vergoz, J. (2022). The multichannel maximum-likelihood (mcml) method: a new approach for infrasound detection and wave parameter estimation. *Geophysical Journal International*, 232(2), 1099–1112. doi: 10.1093/gji/ggac377

- Proud, S. R., Prata, A. T., & Schmauß, S. (2022). The january 2022 eruption of hunga tonga-hunga ha'apai volcano reached the mesosphere. *Science*, 378(6619), 554-557. doi: 10.1126/science.abo4076
- Raspert, R., Abbott, J.-P., Webster, J., Yu, J., Talmadge, C., Alberts II, K., ... Noble, J. (2019). New systems for wind noise reduction for infrasonic measurements. In A. Le Pichon, E. Blanc, & A. Hauchecorne (Eds.), *Infrasound monitoring for atmospheric studies: Challenges in middle atmosphere dynamics and societal benefits* (pp. 91-124). Cham: Springer International Publishing. doi: 10.1007/978-3-319-75140-5_3
- Rost, S., & Thomas, C. (2002). Array seismology: Methods and applications. *Reviews of Geophysics*, 40(3), 2-1-2-27. doi: https://doi.org/10.1029/2000RG000100
- Saito, H., Yasukouchi, Y., Hiratsuka, T., & Yamamoto, M.-y. (2026). First detection of firework-generated infrasound in the upper mesosphere-lower thermosphere with a rocket-borne sensor: Results from the momo3 sounding rocket experiment. *Journal of Geophysical Research: Atmospheres*, 131(8), e2025JD045676. (e2025JD045676 2025JD045676) doi: https://doi.org/10.1029/2025JD045676
- Stratéole-2 c1 campaign dataset. (2021). CNES / Stratéole-2 project. Retrieved from https://doi.org/10.14768/c417e612-015d-4812-9b59-294a6570c7c3 doi: 10.14768/c417e612-015d-4812-9b59-294a6570c7c3
- Van Eaton, A. R., Lapierre, J., Behnke, S. A., Vagasky, C., Schultz, C. J., Pavolonis, M., ... Khlopenkov, K. (2023). Lightning rings and gravity waves: Insights into the giant eruption plume from tonga's hunga volcano on 15 january 2022. *Geophysical Research Letters*, 50(12), e2022GL102341. (e2022GL102341 2022GL102341) doi: https://doi.org/10.1029/2022GL102341
- Vergoz, J., Hupe, P., Listowski, C., Le Pichon, A., Garcés, M., Marchetti, E., ... Mialle, P. (2022). Ims observations of infrasound and acoustic-gravity waves produced by the january 2022 volcanic eruption of hunga, tonga: A global analysis. *Earth and Planetary Science Letters*, 591, 117639. doi: https://doi.org/10.1016/j.epsl.2022.117639
- Walker, K. T., & Hedlin, M. A. (2009). A review of wind-noise reduction methodologies. In A. Le Pichon, E. Blanc, & A. Hauchecorne (Eds.), *Infrasound monitoring for atmospheric studies* (pp. 141-182). Dordrecht: Springer Netherlands. doi: 10.1007/978-1-4020-9508-5_5
- Watson, L. M., Iezzi, A. M., Toney, L., Maher, S. P., Fee, D., McKee, K., ... Johnson, J. B. (2022). Volcano infrasound: progress and future directions. *Bulletin of Volcanology*, 84(5), 44. doi: 10.1007/s00445-022-01544-w
- Waxler, R., & Assink, J. (2019). Propagation modeling through realistic atmosphere and benchmarking. In A. Le Pichon, E. Blanc, & A. Hauchecorne (Eds.), *Infrasound monitoring for atmospheric studies: Challenges in middle atmosphere dynamics and societal benefits* (pp. 509-549). Cham: Springer International Publishing. doi: 10.1007/978-3-319-75140-5_15
- Waxler, R., Hetzer, C., Assink, J., & Velea, D. (2021a). chetzer-ncpa/ncpaprop-release: Ncpaprop v2. 1.0.
- Waxler, R., Hetzer, C., Assink, J., & Velea, D. (2021b, September). chetzer-ncpa/ncpaprop-release: Ncpaprop v2.1.0. Zenodo. Retrieved from https://doi.org/10.5281/zenodo.5562713 doi: 10.5281/zenodo.5562713
- Wescott, J. W. (1964). *Acoustic detection of high-altitude turbulence* (Tech. Rep.).
- Wilmouth, D. M., Østerstrøm, F. F., Smith, J. B., Anderson, J. G., & Salawitch, R. J. (2023). Impact of the hunga tonga volcanic eruption on stratospheric composition. *Proceedings of the National Academy of Sciences*, 120(46), e2301994120. doi: 10.1073/pnas.2301994120
- Wilson, R., Pitois, C., Podglajen, A., Hertzog, A., Corcos, M., & Plougonven, R. (2023). Detection of turbulence occurrences from temperature, pressure, and position measurements under superpressure balloons. *Atmospheric Measurement Techniques*, 16(2), 311-330. doi: 10.5194/amt-16-311-2023

- 1038 Young, E. F., Bowman, D. C., Lees, J. M., Klein, V., Arrowsmith, S. J., & Ballard,
1039 C. (2018). Explosion-generated infrasound recorded on ground and airborne
1040 microbarometers at regional distances. *Seismological Research Letters*, 89(4),
1041 1497-1506. doi: 10.1785/0220180038
- 1042 Zhang, S., Wang, R., Chen, X., Dahm, T., Xu, B., & Zhang, Y. (2025). Mod-
1043 eling atmospheric acoustic-gravity waves from violent volcano eruptions
1044 with seismological approaches. *Journal of Geophysical Research: Solid*
1045 *Earth*, 130(5), e2024JB030911. (e2024JB030911 2024JB030911) doi:
1046 <https://doi.org/10.1029/2024JB030911>
- 1047 Zhu, Y., Mann, G., Newman, P. A., & Randel, W. (2025). *The Hunga Volcanic Erup-*
1048 *tion Atmospheric Impacts Report* (Vol. APARC report 11). Forschungszentrum
1049 Jülich. doi: 10.34734/FZJ-2025-05237
- 1050 Zängl, G., Reinert, D., Rípodas, P., & Baldauf, M. (2015). The ICON (icosahedral
1051 non-hydrostatic) modelling framework of DWD and MPI-M: Description of the
1052 non-hydrostatic dynamical core. *Quarterly Journal of the Royal Meteorological*
1053 *Society*, 141(687), 563-579. doi: <https://doi.org/10.1002/qj.2378>