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Key Points:

- We develop a rapid first-order method to correct the infrasound propagation backazimuth deviation for source location procedures
- We evaluate the method using long-range International Monitoring System data (~700–5,000 km) from the eruptions of Puyehue-Cordón Caulle (2011) and Calbuco (2015)
- We achieve a considerable source mislocation reduction for both eruptions (~75%–85%)

Supporting Information:

Supporting Information may be found in the online version of this article.

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Rapid Location of Remote Volcanic Infrasound Using 3D Ray Tracing and Empirical Climatologies: Application to the 2011 Cordón Caulle and 2015 Calbuco Eruptions, Chile

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Abstract Infrasound (<20 Hz) can propagate thousands of kilometers through the atmosphere, enabling global source location using networks of arrays such as the International Monitoring System infrasound network. However, atmospheric spatiotemporal variability poses a major challenge to locating infrasound sources. Strong horizontal cross-winds deviate the observed infrasound arrival azimuths, producing source mislocations that can be on the order of hundreds of kilometers. We introduce a method that combines empirical climatologies (HWM14/NRLMSIS2.0) and 3D ray tracing (infraGA) to obtain first-order, robust, and rapid estimates of the backazimuth deviations for source location procedures. For each trial source node and receiver path, day of the year and time, we perform an automatic iterative search for infrasound ground intercepts around the target station and obtain the corresponding backazimuth deviation. We test the method using IMS infrasound data from stations up to ~5,000 km range for two similar explosive eruption case studies: 2011 Puyehue-Cordón Caulle and 2015 Calbuco. We obtain a source mislocation reduction up to ~84% (242–38.7 km) and ~75% (366–93.1 km) for Puyehue-Cordón Caulle and Calbuco eruptions, respectively. To evaluate the approach, we repeat the procedure using more realistic hybrid atmospheric descriptions; we obtain comparable results (up to ~75% mislocation reduction for both eruptions). Potential applications of the approach include long-range volcano monitoring in near-real time by using pre-computed look-up tables or large-scale, multi-year reanalyses of infrasound waveform archives.

Plain Language Summary Acoustic waves below the human audible frequency range (20 Hz) are called infrasound. Favorable stratospheric wind conditions allow explosive volcanic infrasound to propagate hundreds to thousands of kilometers. The International Monitoring System (IMS) infrasound network can be used to detect and locate volcanic infrasound sources globally, but the atmospheric winds introduce deviations in the location of the sources that can be up to hundreds of kilometers from true. We introduce a method to generate rapid first-order azimuth corrections to tackle this issue, and test it with data from 2011 Puyehue-Cordón Caulle and 2015 Calbuco eruptions, Chile. We use infrasound detections from the nearest eight IMS stations to both volcanoes (~1,500 to ~5,000 km), obtaining significant improvements of the source locations (up to ~84% mislocation reduction). Upon further testing, this method could be used to improve long-range volcano monitoring in near-real time or large-scale, multi-year reanalyses of infrasound waveform archives.

1. Introduction

Detecting, quantifying, and cataloging the global occurrence of explosive volcanism helps toward several goals in Earth sciences and has direct applications in volcanic hazard mitigation (Matoza et al., 2019, and references therein). Previous work has demonstrated that infrasound arrays can be used to detect, locate, and provide detailed chronologies of remote explosive volcanism, with the potential to provide source parameters for ash transport and dispersal models (e.g., Caudron et al., 2015; Dabrowa et al., 2011; Fee et al., 2010; Garcés et al., 2008; Green et al., 2013; Marchetti et al., 2019; Matoza et al., 2007; Matoza et al., 2018; Matoza, Le Pichon et al., 2011; Matoza, Vergoz, et al., 2011; Perttu et al., 2020; Ripepe et al., 2018; Taisne et al., 2019). Regional volcano-acoustic monitoring and early warning systems are being investigated and implemented (De Angelis et al., 2012; Fee et al., 2010; Garcés et al., 2008; Kamo et al., 1994; Matoza et al., 2007; Ripepe et al., 2018; Taisne et al., 2019). Recent work has explored the potential of the International Monitoring System (IMS) infrasound network to provide a quantitative catalog of global explosive volcanic activity (Matoza et al., 2017) and automated eruption notifications to Volcanic Ash Advisory Centers (VAACs) (Mialle et al., 2015).

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Required elements of a processing workflow to achieve these goals include infrasound signal detection, discrimination, association, and location (e.g., Arrowsmith et al., 2008; Arrowsmith et al., 2015; Arrowsmith & Whitaker, 2008; Brachet et al., 2010; Brown et al., 2002; Evers & Haak, 2005; Le Pichon et al., 2008; Modrak et al., 2010; Park et al., 2014; Sanderson et al., 2020). Challenges to each processing stage result from strong signal variability associated with long-range acoustic propagation through the temporally and spatially varying atmosphere (e.g., J. Assink et al., 2019; Drob, Garcés, et al., 2010; Le Pichon et al., 2009; Green & Bowers, 2010; Nippres et al., 2014; Waxler et al., 2017), and from widely varying incoherent wind noise (e.g., Walker & Hedlin, 2010) and coherent ambient infrasound (clutter) interfering sources (Matoza et al., 2013, 2019).

Here, our emphasis is on developing a method that could be applied rapidly to produce near-real-time analysis products to aid volcano monitoring, or that could be applied automatically and systematically to large data archives. Thus, we seek to provide rapid, first-order location solution estimates using automated procedures that do not require downloading and manipulating large realistic atmospheric specification products, emphasizing rapid and efficient computation speed over atmospheric and infrasound propagation realism (e.g., Schwaiger et al., 2019; Smets et al., 2015, 2016).

Stratospheric and lower mesospheric zonal winds have a strong influence on the observed wave parameters of infrasound detections (e.g., Drob, Meier, et al., 2010; Evers & Haak, 2005; Garcés, 2004; Le Pichon, Blanc, & Drob, 2005; Le Pichon, Blanc, Drob, et al., 2005; Le Pichon et al., 2006). At mid-to-high latitudes especially, the cross-winds at stratospheric heights become a primary factor controlling global infrasound source mislocation (e.g., Evers & Haak, 2005; Matoza, Le Pichon et al., 2011; Mialle et al., 2019), which has been up to hundreds of kilometers from true for IMS case studies (e.g., Evers & Haak, 2005; Matoza et al., 2017, 2019). A common approach for assessing the expected source mislocation is to forward-model the atmospheric effects on the infrasound detections (e.g., J. D. Assink et al., 2014; Arrowsmith et al., 2007; Le Pichon et al., 2009; Green et al., 2011; Marcillo et al., 2014; Matoza et al., 2018).

Atmospheric infrasound propagation modeling requires specifications of temperature, wind velocity, density, and molecular composition from the ground surface up to ~140 km altitude. To model infrasound propagation, these specifications are typically obtained in three main ways: (a) using data assimilation analyses such as the European Center for Medium-Range Weather Forecasting (ECMWF), which gathers ground-based and meteorological data as constraints to physically model the atmosphere from the ground to ~80 km in altitude every 6-hr; (b) empirical climatologies, which use multidecadal historical archives of the atmospheric data to statistically represent the atmosphere from the ground to the exobase (~750 km) with 12-hr intervals (e.g., the Horizontal Wind Model (HWM) (Drob et al., 2015) and the NRLMSIS2.0 model (Emmert et al., 2020); or (c) hybrid models that seamlessly integrate both approaches (e.g., the Naval Research Laboratory Ground to space (G2S) [Drob et al., 2003], or AVO-G2S [Schwaiger et al., 2019]). The most recent trend in infrasound studies is toward increasing propagation realism and accuracy (more accurate characterization of atmospheric state and finer spatio-temporal scales), implementing either data assimilation analyses or hybrid models (e.g., Ceranna et al., 2009; Fee et al., 2020; Smets et al., 2015). However, this comes with the cost of a greatly increased computational burden that can quickly escalate for global models and/or multi-decadal studies. Empirical climatologies, on the other hand, are succinct self-contained programs that reduce computational needs to a minimum, but generally underrepresent smaller scale atmospheric variations (e.g., stratospheric zonal jets) (Drob et al., 2003). Here we explore the potential of using empirical climatologies for a first-order “good enough” estimate of stratospheric cross-wind corrections for rapid infrasound signal association and source location, with the goal of real-time application or retrospective systematic reanalyses of large multi-decadal data archives. Our approach builds on that of pre-computed look-up tables, generally based also on empirical climatologies (e.g., Drob, Garcés, et al., 2010; Morton & Arrowsmith, 2014).

Matoza et al. (2017) introduced a signal association and location method algorithm (IMS_vASC), which uses array processing results from the global IMS infrasound network to automatically detect and catalog global multi-year (2005–2010) explosive volcanic signals. In this paper, we aim to incorporate first-order rapid corrections of the cross-winds effects on this trial source location process. Thus, we explore the use of empirical climatologies combined with infraGA 3D ray tracing (Blom & Waxler, 2012) to estimate the backazimuth deviation produced by the cross-winds for a large grid of trial source locations on the Earth's surface. Since infrasound propagation strongly depends on ducting conditions, we also investigate the use of a simplified Gaussian wind jet parameterization (Jones (1986) HARPA user manual) to perturb the climatology profiles and force a stratospheric or thermospheric return within reasonable bounds for the wind strength.

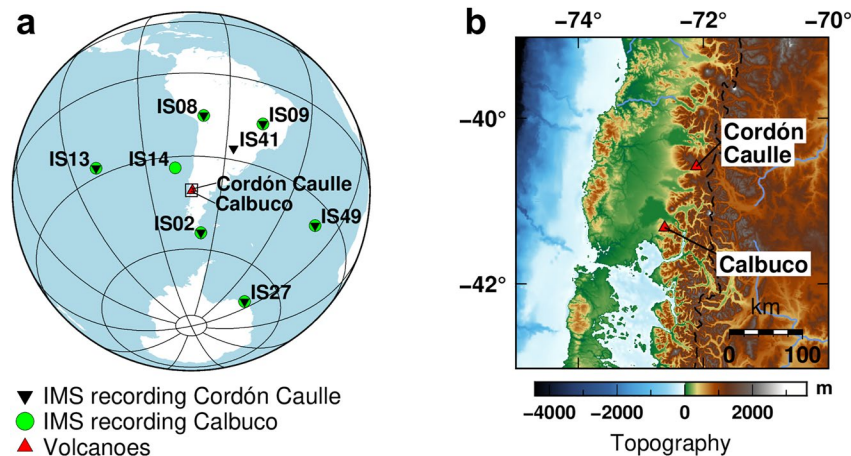


Figure 1. Location of International Monitoring System (IMS) stations and volcanoes. (a) Black inverted triangles: IMS stations that were recording during 2011 Puyehue-Cordón Caulle volcanic complex (Cordón Caulle) eruption. Green circles: IMS stations that were recording during the 2015 Calbuco eruption. Red triangles: PCCVC and Calbuco locations. Black rectangle indicates the zoomed area in (b). (b) Topographic map of the zoomed area of volcanoes (red triangles). Black-dashed line: border between Chile and Argentina.

In Section 2, we present two similar explosive eruption event case studies that we use to assess the method. In Section 3, we introduce the methodology to model the backazimuth deviations, as well as possible improvements to deal with the oversimplification of the lower atmospheric descriptions. In Section 4, we summarize our findings in reducing the source mislocation with IMS_vASC and compare the effects of choosing different atmospheric descriptions and modeling parameters. In Section 5, we discuss the feasibility of the method to obtain first-order approximations for global infrasound backazimuth deviations.

2. Data

2.1. Volcanic Setting

Puyehue-Cordón Caulle volcanic complex is a Pleistocene-Holocene active area composed of three volcanoes: Cordillera Nevada caldera ($\sim 1,000$ m a.s.l.), Cordón Caulle fissure system ($\sim 1,500$ m a.s.l.), and Puyehue stratovolcano ($\sim 2,000$ m a.s.l.). It is located in the southern Andes volcanic zone, inside Puyehue National Park, Los Lagos Region, Chile (-40.5828° , -72.1122°). Since the Late Pleistocene, Cordón Caulle has been the only active volcano, with at least three eruptions in the last century (1921, 1960 and 2011) (Elissondo et al., 2016). On 4 June at 18:45 UTC, 2011, after two months of increasing seismicity, the eruption started with an explosive event that generated a plume of ~ 9 – 12 km high (Collini et al., 2013; Elissondo et al., 2016). This paroxysmal plinian/subplinian phase lasted about 2 days, followed by a period of about 2 months with a fluctuating activity that resulted in sustained column heights between 4 and 12 km.

Calbuco volcano, Chile (-41.3300° , -72.6183°) is a $\sim 2,000$ m a.s.l. stratovolcano located at about 100 km SW from Cordón Caulle (Global Volcanism Program, 2013). On 22 April 2015, at 21:05 UTC, Calbuco started a subplinian/plinian explosive phase after a relatively short period of shallow seismic precursor activity, sending ash to an altitude of 15 km. The maximum intensity of the eruption was reached on April 23, with a phase of 6 hr in which column height reached 17 km (Castruccio et al., 2016; Matoza et al., 2018; Van Eaton et al., 2016). The intensity decreased rapidly after this phase, falling back into a pre-eruptive activity regime in about a month.

Cordón Caulle and Calbuco eruptions occurred at similar altitudes ($\sim 2,000$ and $\sim 1,500$ m, respectively) and locations, under strong zonal mid-latitude eastward winds (see Figure 1; see also Figures S6 and S7 in Supporting Information S1). Both eruptions were cataloged as VEI 4 (volcanic explosivity index, [Newhall & Self, 1982]), with sustained plume heights of more than 10 km that lasted several days (Castruccio et al., 2016; Collini et al., 2013; Elissondo et al., 2016; Van Eaton et al., 2016), and occurred during atmospheric stratospheric winds prevailing toward the East.

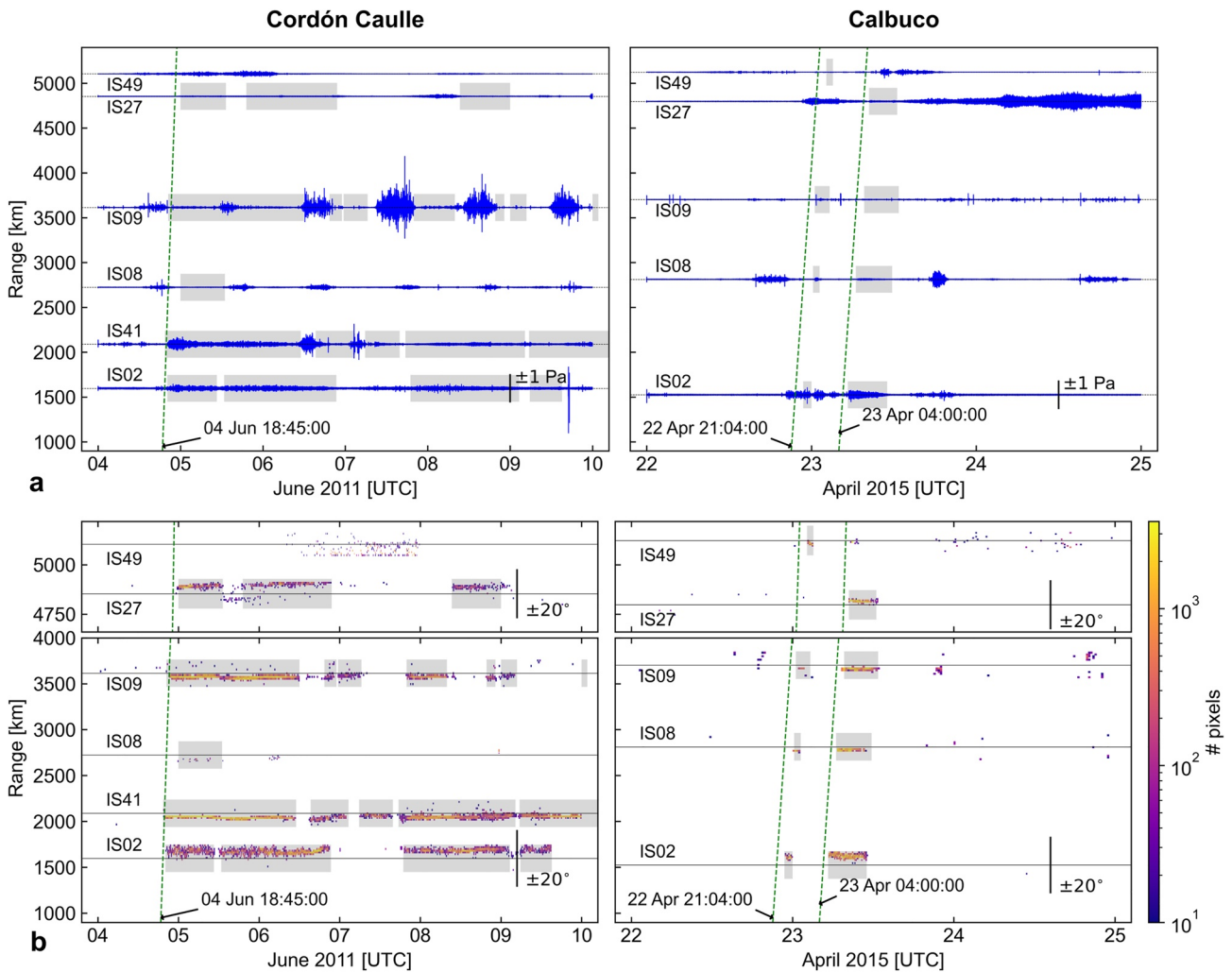


Figure 2. (a) Beamformed waveforms ($0.5 < f < 5$ Hz) for each station array, except upwind and non-recording stations (IS13, IS14, and IS41 for Calbuco only). In a gray background, we depict the associated detections attributable to the source in (b). In green slanted dashed lines, we show the estimated arrival time ($c = 300$ m/s) of the acoustic wave with origin time on each eruption's onset. (b) Progressive Multichannel Cross-Correlation (PMCC) detections from all available stations for Cordón Caulle (left) and Calbuco (right) volcanoes. For each station, we display a 2-D histogram that shows the number of pixels of parsed ($0.5 < f < 5$ Hz) PMCC detections in time (x-axis) by azimuth relative to the geographical station-to-source value (y-axis). Only values in the range $\pm 20^\circ$ for each station have been considered.

2.2. IMS Data

The IMS network is the main monitoring infrastructure of the Comprehensive Nuclear-Test-Ban Treaty Organization, integrating seismic, hydroacoustic, infrasonic, and radio nucleoid detection technologies. The IMS infrasound network currently has 53 (of 60 planned) stations detecting coherent acoustic waves that could be generated by explosions down to 1 kt of TNT anywhere on Earth (Christie & Campus, 2010). Each IMS station is composed of at least four microphone sensors with a flat response from 0.02 to 4 Hz within 3 dB. At the International Data Center of the CTBTO (Vienna, Austria) the raw waveforms from all IMS stations are processed with the Progressive Multichannel Cross-Correlation method algorithm (PMCC) (Cansi, 1995; Cansi & Klinger, 1997) in real-time, generating detection lists.

For this study, we considered the nearest eight IMS infrasound stations to both volcanoes (see Figure 1), which range from $\sim 1,600$ (IS02, Argentina) to $\sim 5,100$ km (IS49, United Kingdom). We downloaded the available IMS waveforms in a time window of 20 days, centered at each eruption time. We use PMCC to extract coherent detections for further analysis (see Figure 2 for a glance at the most interesting sequences). We implemented PMCC with 15 log-spaced frequency bands between 0.01 and 5 Hz, following Matoza et al. (2013).

We note that during the Cordón Caulle eruption (2011), the station IS14 was not operational after the destructive effects of the tsunami generated by the Chilean M8.8 Maule earthquake on 27 February 2010. Similarly, during Calbuco eruption (2015), station IS41 could not provide detections due to a reduced number of detecting channels (see Figure 1). We discuss the effects of the consequent station distribution difference in Section 5.

3. Methods

IMS_vASC is a brute-force, grid-search, cross-bearings method (Matoza et al., 2017) to localize sustained explosive volcanic infrasound signals with the IMS infrasound network of arrays. It enhances sources that have a sustained but limited time span (i.e., volcanic eruptions) by cleaning unwanted background detections (clutter) from the data. It localizes the source by performing cross-bearings for the nearest detecting stations with the backazimuth information of the cleaned detections. Although this approach takes advantage of the IMS infrasound network capabilities, atmospheric winds in the propagating path of the signals can considerably alter their apparent backazimuths and detectability (see Figure 3), causing source mislocations up to hundreds of kilometers (e.g., Drob, Meier, et al., 2010; Evers & Haak, 2005; Garcés, 2004; Le Pichon, Blanc, & Drob, 2005; Le Pichon, Blanc, Drob, et al., 2005; Le Pichon et al., 2006). IMS_vASC allows the use of backazimuth correction values in the source location process, but lacks a robust process to implement it. Thus, we aim to estimate the expected backazimuth deviations by modeling infrasound propagation under reasonable atmospheric conditions, providing IMS_vASC with a set of corrections to reduce the source mislocation. Once some basic parameters are defined (e.g., source and station locations, time, etc.), our approach automatically performs an iterative calculation of expected backazimuths (if any) by modeling infrasound propagation with 3D ray tracing (infraGA) (Blom & Waxler, 2012), and an empirical set of atmospheric descriptions obtained from a combination of the Horizontal Wind Model (HWM14) (Drob et al., 2015) and the Mass Spectrometer Incoherent Radar Model (NRLMSIS2.0) (Emmert et al., 2020).

3.1. Modeling the Atmosphere

3.1.1. Raw Climatologies

The “raw” climatological descriptions refer to the default atmospheric model obtained by combining HWM14 and NRLMSIS2.0. For each source-station direction and time, we obtain the horizontal winds (i.e., zonal and meridional), temperature, density, and pressure values every 50 km. For heights from 0 to 170 km in steps of 0.5 km, we average each parameter along the source-station direction, thus obtaining one set of estimations per height. The resulting model will be a layered range-independent atmosphere representative of each ray propagation direction, which is saved in tables (1D profiles) that will be used by the ray tracing algorithm to model infrasound ray propagation on a 3D spherical layered atmosphere. For the next atmospheric model types, the discretization follows the same procedure.

The strong assumption of a range-independent atmosphere is a reasonable first-order approximation that allows a reduced computational cost for 3D ray tracing propagation (see the infraGA/geoAC manual). As we use real observations to evaluate the validity of our approach, the comparison with more realistic but computationally demanding models (e.g., range-dependent ray propagation) should be considered in future developments (e.g., see Figure S19 in Supporting Information S1).

For this study, the eruption times are 2011-06-04 at 19:00 UTC for Cordón Caulle, and 2015-04-22 at 21:00 UTC for Calbuco.

In addition to the raw empirical climatologies used by default, we explore perturbing the wind values obtained with HWM14 to enhance along-path stratospheric winds in a simplified manner.

3.1.2. Perturbed Climatologies

Numerous case studies (e.g., Arrowsmith et al., 2007; J. D. Assink et al., 2014; Ceranna et al., 2009; Evers & Haak, 2007; Green et al., 2011; Lalande & Waxler, 2016; Le Pichon et al., 2015; Smets et al., 2016) have shown that long-range infrasound detection is often dependent on marginal ducts. Smoothed atmospheric profiles available in both weather reanalysis products and climatologies fail to capture small-scale fluctuations on which infrasound propagation depends, thus controlling detection versus non detection for a source-receiver pair

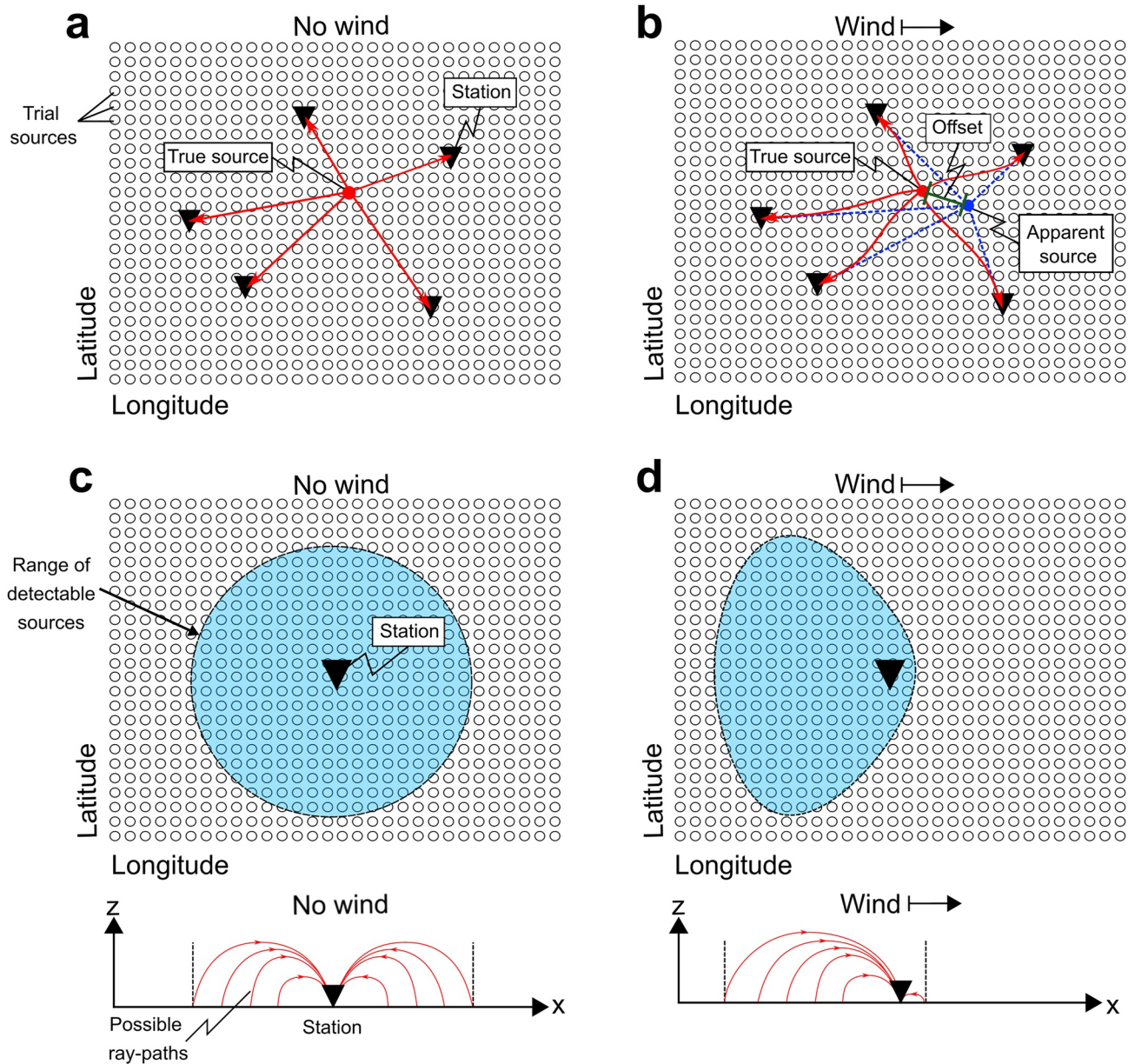


Figure 3. Effect of stratospheric winds on the source offset (top) and the source detectability (bottom). The stations are depicted as black inverted triangles, while the possible trial sources as a grid of white circles surrounding them. (a) A source (red circle) produces signals that travel undisturbed to each station (no wind present). (b) The moving medium (i.e., winds) bends the ray paths (red). Under winds blowing from west to east, the source seems to be shifted eastwards when performing cross-bearing locations with the apparent backazimuths (blue dashed line), producing an offset. (c) Without winds, the detectable sources should be inside the light-blue circle around the station (black triangle). (d) With wind blowing from west to east as shown in this figure, the detectable range is now enhanced in the downwind direction from the trial sources or similarly the upwind direction from the station (i.e., here more trial sources to the West of the station are possible candidates for signals detected by the station). Conversely, the detectable range is reduced in the downwind direction (East) from the station (corresponding to the upwind direction from these trial sources East of the station toward this station). Cartoons of example ray paths in 2D show how the wind affects detectability at the bottom of (c and d).

(e.g., Matoza, Le Pichon et al., 2011). A fundamental limit of the climatologies used in this study is that they tend to underestimate the atmospheric propagation ducts. In prior studies, this issue has been tackled by using gravity-wave perturbations of the profiles to obtain more realistic infrasound arrivals (ground intercepts) (e.g., Gibson et al., 2009; Green et al., 2011; Kulichkov et al., 2010; Norris et al., 2010; Smets et al., 2016). However, this type of approach tends to be computationally expensive, departing from our rapid first-order main goal. Instead, we investigate the use of a simplified parametric Gaussian wind jet (Jones, 1986) perturbation to enhance the stratospheric winds that could cause ducting (see Figure 4). The perturbation is centered at 40 km of altitude,

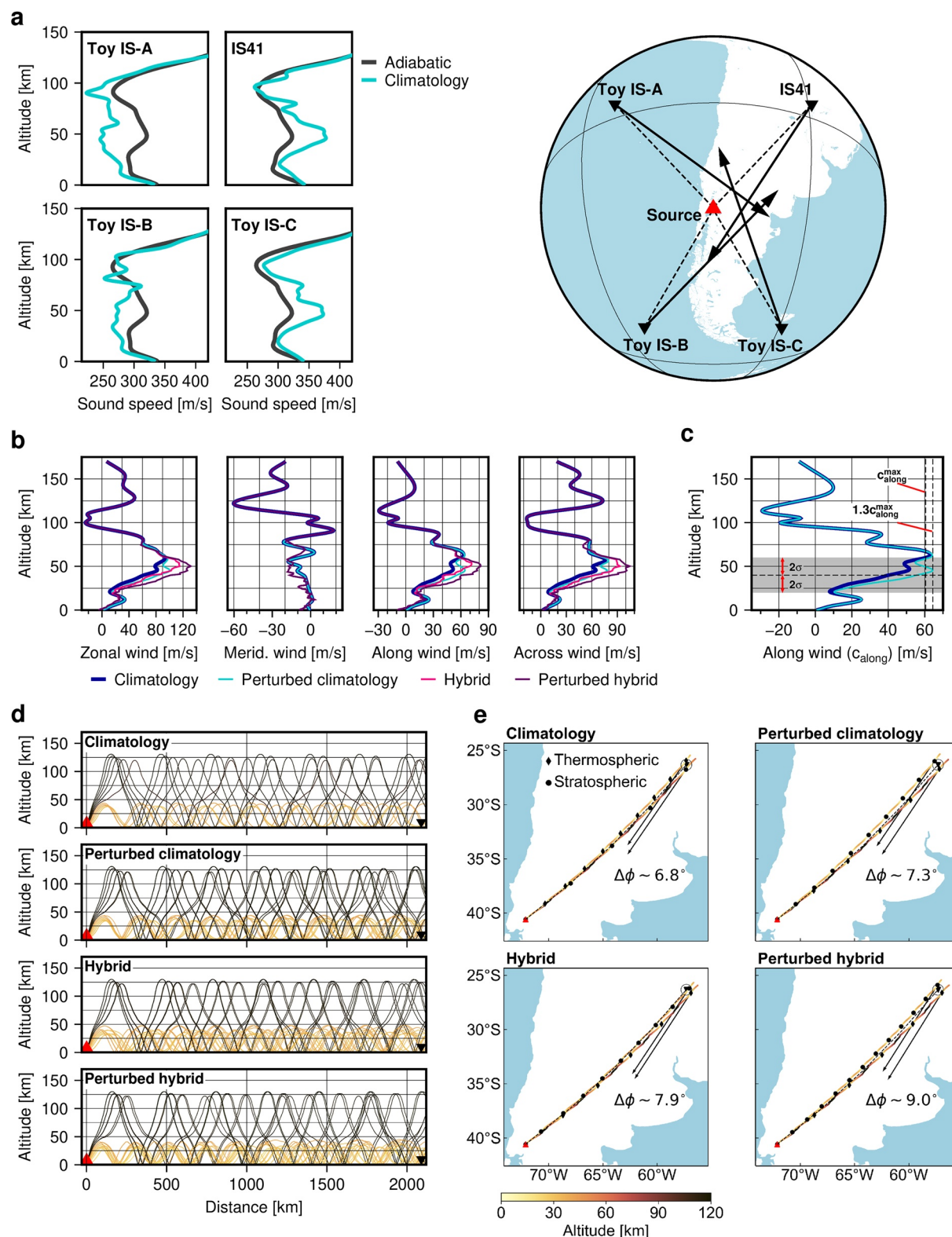


Figure 4.

with a standard deviation of 10 km, and amplitude equivalent to 30% of the maximum effective speed (see Equation 1) in this altitude range (~20–60 km; see Figures 4c and 4d). Additionally, the perturbation is applied only when positive along-path winds are present at these altitudes to avoid creating unrealistic zonal ducts.

$$c_{eff} = c_T + \hat{n} \cdot \vec{c}. \quad (1)$$

where $\vec{c} = (u, v)$ is the wind speed in height, with u and v the zonal and meridional winds, respectively; $\hat{n}$ is the propagation direction from the source to the station; and c_T is the adiabatic sound speed in height.

We note that this simplified wind perturbation approach is justifiable given the method application in a grid-search source location procedure (Matoza et al., 2017). In this procedure, a trial source node is only illuminated if there are corresponding observed detections at multiple stations. Thus, the Gaussian wind jet is simply a tool to help assess if a given trial source node is feasible for a given set of infrasound observations given reasonable deviations of the atmospheric profiles.

We assess how the raw and perturbed climatologies results compare to more realistic atmospheric descriptions corresponding to a hybrid model based on the European Centre for Medium-Range Weather Forecasts (ECMWF) descriptions.

3.1.3. Hybrid Model

We build a hybrid set of descriptions by merging the ECMWF reanalysis v5 (ERA5) data for the model reference levels (137 levels from ~0 to ~80 km altitude) with empirical climatologies (>80 km altitude) in height (see Figure 4). We download ERA5 descriptions of horizontal winds and temperature for the area and time of interest, and complete the descriptions in height with the empirical climatologies using a simple linear interpolation of the averaged in values per height. This results in more realistic wind and temperature descriptions under ~80 km altitude for the infrasound raypaths (i.e., small tropospheric or stratospheric ducts), completed above ~80 km with the robust but coarser climatological descriptions (See Figures S2–S5 in Supporting Information S1).

3.1.4. Perturbed Hybrid Model

We also calculate a set of perturbed hybrid profiles following the same procedure as in Section 3.1.2. In this case, the resulting descriptions will not match the realistic model, but could account for other type of phenomena that are still not present in the ERA5 profiles (i.e., gravity waves types of perturbations).

Once the atmosphere model is defined, we continue with an iterative approach to determine the backazimuth deviation for each source-station pair.

3.2. Iterative Backazimuth Deviation Estimation

For a given trial source node and receiver (station) pair, we begin by using infraGA 3D ray tracing to launch two sets of rays, with azimuths ϕ_1 and ϕ_2 , that azimuthally enclose the station location (see Figure 5, left panel). The launch azimuths are modified iteratively to converge to a value where it is possible to obtain ground intercepts or to otherwise declare the case as “ill-conditioned” (no ground arrivals near the station). Both sets of rays, with corresponding backazimuths φ_1 and φ_2 , are launched with inclinations from 0.5° to 40.0° in steps of 0.5°. If the ground intercepts (depicted as white circles in 5, left panel) have a great-circle annular distance smaller than the threshold value, d_r (0.5° for this study), their backazimuths are averaged and used as a starting value to launch the next iteration. The next launching azimuths, ϕ'_1 and ϕ'_2 , are modified to reduce the great-circle radial distance from the average location of ground intercepts to the receiver, d_ϕ (Figure 5, right panel). This process continues until d_ϕ is reduced below a threshold value (0.05° for this study). Once the ground intercepts are near enough to

Figure 4. (a) Right: example case of cross-bearings for Cordón Caulle location (red triangle) during predominant Winter-like eastward zonal winds (the only real infrasound station is IS41). Here the source appears to be East of the true source location. In black arrows: modeled backazimuth from each station. In black-dashed lines: geographical azimuths from Cordón Caulle to each station (black inverted triangles). Left: reference average sound speed profiles in altitude calculated with empirical climatologies for each station. (b) Reference zonal, meridional, along-path, and across-path atmospheric winds in altitude for Cordón Caulle to IS41 direction, from empirical climatologies (blue line), perturbed climatologies (cyan line), hybrid (purple), and perturbed hybrid descriptions (pink). (c) Close-up comparison between empirical climatologies and perturbed climatologies, showing the heights where the empirical climatologies are perturbed to match $1.3 \times c_{along}^{max}$ (~20–60 km). (d) Comparison of ray tracing results for IS41 using the atmospheric descriptions in (b). The selected rays are colored by turning altitude (see color bar at bottom right). (e) Overhead maps with a stratospheric and a thermospheric ray from (d). The rays are colored by altitude. The backazimuth deviations of each ray at IS41 ($\Delta\phi$) are depicted by black arrows, while the average azimuth deviation is indicated numerically in the map as well. The black dots and diamonds represent the stratospheric and thermospheric ray ground intercepts, respectively.

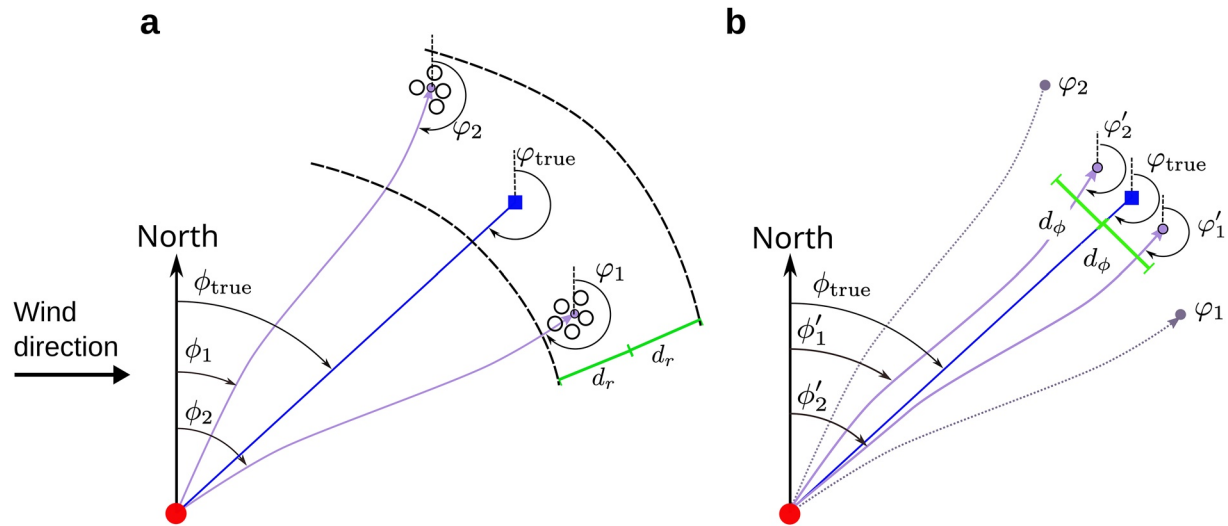


Figure 5. Iterative backazimuth deviation estimation for an a priori known source location (red dot). (a) The source has a geographical azimuth (blue line), or “true azimuth,” toward the receiver (blue square). First, we launch two sets of rays (purple curved lines) with azimuths, ϕ_1 and ϕ_2 , containing the true azimuth, ϕ_{true} . The curvature of the launched rays represents the effect of eastward winds (black arrow on each subplot), introducing a backazimuth deviation. If the ground intercepts (white circles) are inside an annular area of width $2d_r$ (green intervals), their average (purple dot) is used to obtain their respective backazimuths, ϕ'_1 and ϕ'_2 . (b) Next, we reduce the angular distance and recalculate the backazimuths as in (a). The new launch azimuths (ϕ'_1 and ϕ'_2) still contain the true azimuth (ϕ_{true}), and should be inside the annular area in (a). We repeat this process iteratively until the desired threshold, d_ϕ , is reached. The final backazimuths, ϕ'_1 and ϕ'_2 , are averaged to determine the backazimuth deviation, $\Delta\phi$, for the source-receiver pair.

the receiver, their average properties are calculated and used to determine the modeled backazimuth, ϕ_{app} . If a maximum number of attempts is exceeded during the search process (40 in this study), the case is also declared to be “ill-conditioned”, reflecting atmospheric conditions that in practice will impede infrasound detections at the station (e.g., strong stratospheric winds that oppose the propagation direction). Finally, the backazimuth deviation, $\Delta\phi$, is calculated as the difference between the geographical backazimuth, ϕ_{true} , and the modeled backazimuth, ϕ_{mod} (i.e., $\Delta\phi = \phi_{true} - \phi_{mod}$).

We note that infraGA includes an eigenray search method that could be used for determining ray parameters as we did in this study. However, at the propagation ranges we consider (~ 700 to $\sim 5,000$ km), the infraGA search method will be unable to find arrivals at the target stations, which is essentially due to the increasing launch angle sensitivity with range. Different approaches could also be used to deal with this issue (e.g., Blom, 2020).

4. Results

4.1. Waveforms and PMCC Detections

We display the waveforms and PMCC detections from the IMS stations considered in this study in Figure 2 from 1 day before each eruption onset to 5 days after for Cordón Caulle and 2 days after for Calbuco. We note IS41, the station with the longest PMCC detection sequence during Cordón Caulle eruption (Figure 2b, left), was not recording during Calbuco eruption (Figure 2b, right). Additionally, the lack of IS13 and IS14 records from Figure 2 was a choice to emphasize the most relevant stations detections, despite their datasets being still considered in our analysis (see Figure S1 in Supporting Information S1). The prevalence of strong eastern stratospheric winds during both eruptions (see Figures S6 and S7 in Supporting Information S1) made these stations unable to detect long-range infrasound coming from the east (i.e., upwind sound propagation).

The expected arrival times of the observed explosive eruption phases (Castruccio et al., 2016; Collini et al., 2013; Elissondo et al., 2016; Van Eaton et al., 2016) for celerities of 300 m/s across the stations (green dashed lines) help visualize the difference between the background PMCC detections before and after volcanic activity. For both volcanoes, the eruptive onset can be observed in at least four stations. These are IS02, IS41, IS09, and IS49 for Cordón Caulle; and IS02, IS08, IS09, and IS49 (first explosion) or IS27 (second explosion). On the other hand, it is clear that much of the observable waveforms do not match the coherent volcanic detections (gray boxes in Figure 2a).

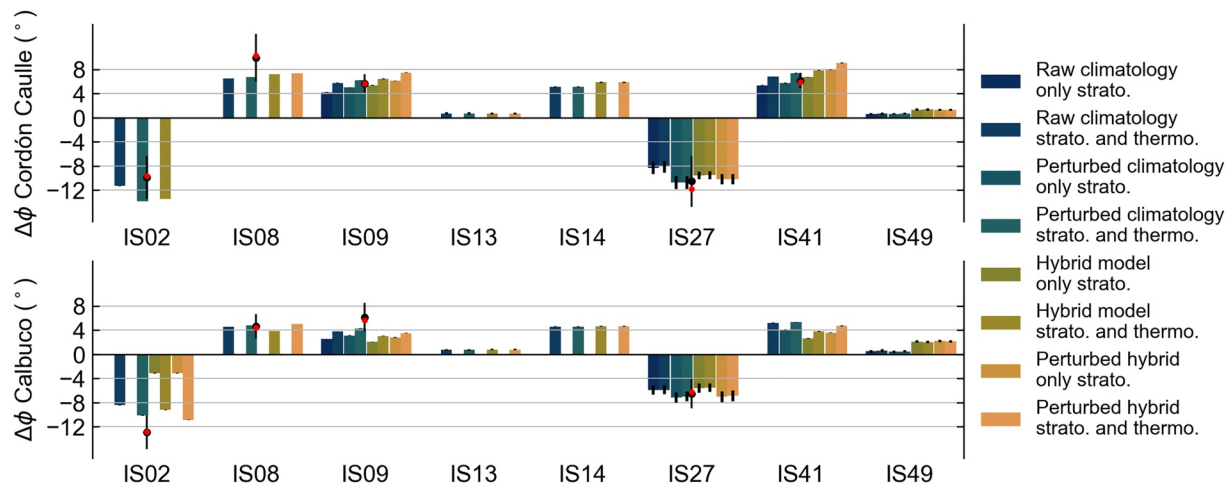


Figure 6. Comparison of backazimuth deviation results modeled for all considered stations for both eruptions. Each result is a combination of the model choices described in Section 3.1 using only arrivals that turned at stratospheric heights (“only strato.”), or using arrivals that have both stratospheric and thermospheric turning heights (“strato. and thermo.”). Each bar represents the backazimuth deviation value (see Section 3.2). Some of the stations do not have an associated backazimuth deviation, indicating the method does not converge. Each bar has a standard deviation size range indicated on a black vertical line. For the stations IS02, IS08, IS09, IS27 for both volcanoes, and IS41 for Cordón Caulle only, we show the real backazimuth deviation mean (black dot), median (red dot), and standard deviation (vertical black line) for the first two days since each eruption (Figure 2; Figures S11 and S12 in Supporting Information S1).

The general backazimuth deviation of the detections is similar for both eruptions, with stronger effects due to higher regional zonal winds for Cordón Caulle (June 2011) than Calbuco eruption (April 2015) (see Figures S2–S5 in Supporting Information S1 for effective sound speed profiles; also S6 and S7 for average zonal winds in area of study). The station coverage is affected by the zonal wind conditions, generating an azimuthal gap of detecting stations of ($\sim 200^\circ$) on the western quadrant (IS02–IS08). The eastern quadrant stations (i.e., downwind signal propagation) have an azimuthal gap of $\sim 107^\circ$ instead (from IS09 to IS27), and carry the bulk of the detection information that will be used to find the most probable source location.

An evident difference between Cordón Caulle and Calbuco eruptions (Figure 2b) is that the PMCC infrasound detections last for at least 5 days for the former, while only some hours for the latter. The apparent source locations for both eruptions should be then determined by similar wind effects, but with a better station coverage (IS41) and a considerably higher number of detections for Cordón Caulle than Calbuco.

4.2. Predicted Backazimuth Deviations

For each atmosphere model defined in Section 3, we run a simulation to estimate the backazimuth deviation at each station for signals coming from both eruptions (Figure 6). Additionally, we classify our results by the turning height of the ground intercepts, labeling them as “only strato.” when only using rays with stratospheric turning heights (< 60 km), or “strato. and thermo.” when also including ground intercepts with thermospheric turning heights (usually ~ 120 km).

The modeled backazimuth deviations are positive (i.e., observed azimuth is smaller than the true azimuth) when the source-station direction has a north component, and negative (i.e., observed azimuth is bigger than true) on the opposite case, matching the observed deviations in Figure 2. The backazimuth deviation magnitudes range from $\sim 1^\circ$ (IS49) to $\sim 12^\circ$ (IS02), with higher values for Puyehue-Cordón Caulle (~ 2 to $\sim 12^\circ$) than for Calbuco (~ 1 to $\sim 10^\circ$), in concordance with stronger eastward zonal winds for June than April in the area of study (See Figures S6 and S7 in Supporting Information S1).

Near all “strato. and thermo.” cases successfully provided deviation values, although IS13 and IS14 have associated deviations with extreme arrival transmission losses (see Figures S8 and S9 in Supporting Information S1) that render their predictions invalid for data correction purposes.

When “only strato.” and “strato. and thermo.” models give deviation estimates, we see the values are comparable, with generally smaller magnitudes for “only strato.” results (e.g., IS90, IS27, IS41, or IS49). The exception to this rule is IS02 for Calbuco when using a hybrid model, where a strong tropospheric jet, invisible for the

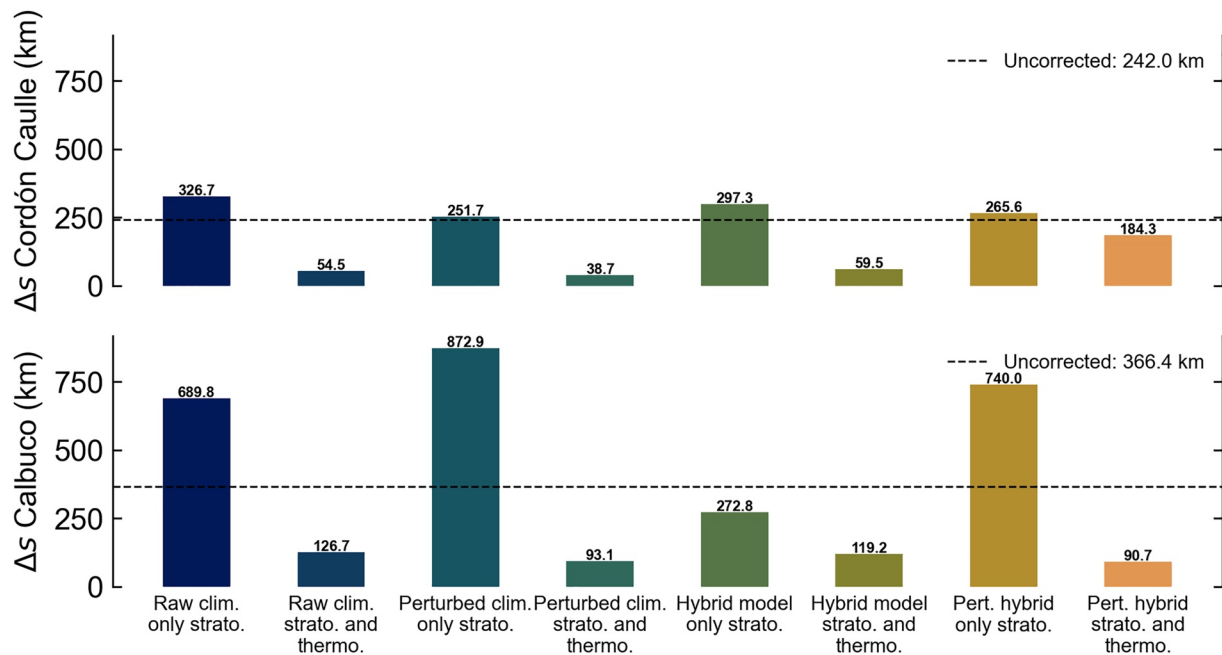


Figure 7. Summary of modeled source location offsets (km) using IMS_vASC for each combination of choices (see Figure 6). In a black-dashed line, we depict the offset when no corrections are used (i.e., “uncorrected”).

climatologies, allows arrivals with a much smaller backazimuth deviation (see Figures S4 and S5 in Supporting Information S1).

For cases with enough detections and clear bell-like distributions (see Figures S11 and S12 in Supporting Information S1) we included estimations of the observed backazimuth deviation mean, median, and standard deviation in Figure 6 (IS02, IS08, IS09, and IS27 for both volcanoes, while IS41 only for Cordón Caulle). We see a general agreement of the observed mean and medians with the predicted values across all models, but especially the perturbed cases, as they produce higher backazimuth deviations. The climatologies compare well with the hybrid models, with backazimuth deviations that differ by $\sim 1\text{--}2^\circ$.

4.3. Source Locations

We first calculated the uncorrected (straight ray great-circle path assumption) source location with IMS_vASC, finding a mislocation of ~ 242 km for Puyehue-Cordón Caulle eruption that increased to ~ 366.4 km for Calbuco eruption (Figures 7 and 8). These values represent the baseline mislocation due to atmospheric conditions during each eruption.

After using the modeled backazimuth deviations (Figure 6) as correction values for IMS_vASC, we observe that regardless of the atmospheric model used, the mislocations reduce for all the “strato. and thermo.” results (Figure 7), but almost always increase for the “only strato.” results (only the Hybrid model reduces the mislocation).

For the Puyehue-Cordón-Caulle case, the ~ 242 km original offset reduces from $\sim 24\%$ (~ 184.3 km, “Hybrid pert. strato. and thermo.”) to $\sim 84\%$ (~ 38.7 km, “Perturbed clim. strato. and thermo.”). For Calbuco case (~ 366.4 km), the reduction ranges from $\sim 65\%$ (~ 126.7 km, “Raw clim. strato. and thermo.”) to $\sim 75\%$ (90.7 km, “Pert. hybrid strato. and thermo.”).

The association and location method, IMS_vASC, also finds the nearest Holocene potentially active volcano (Global Volcanism Program, 2013) after calculating the apparent location of the source. In Table 1, we summarize the apparent source and nearest active volcano mislocations to the actual targets. The climatological corrections have comparable mislocation reduction results with the hybrid corrections, with better results than the hybrid model when using perturbed climatologies with stratospheric and thermospheric arrivals.

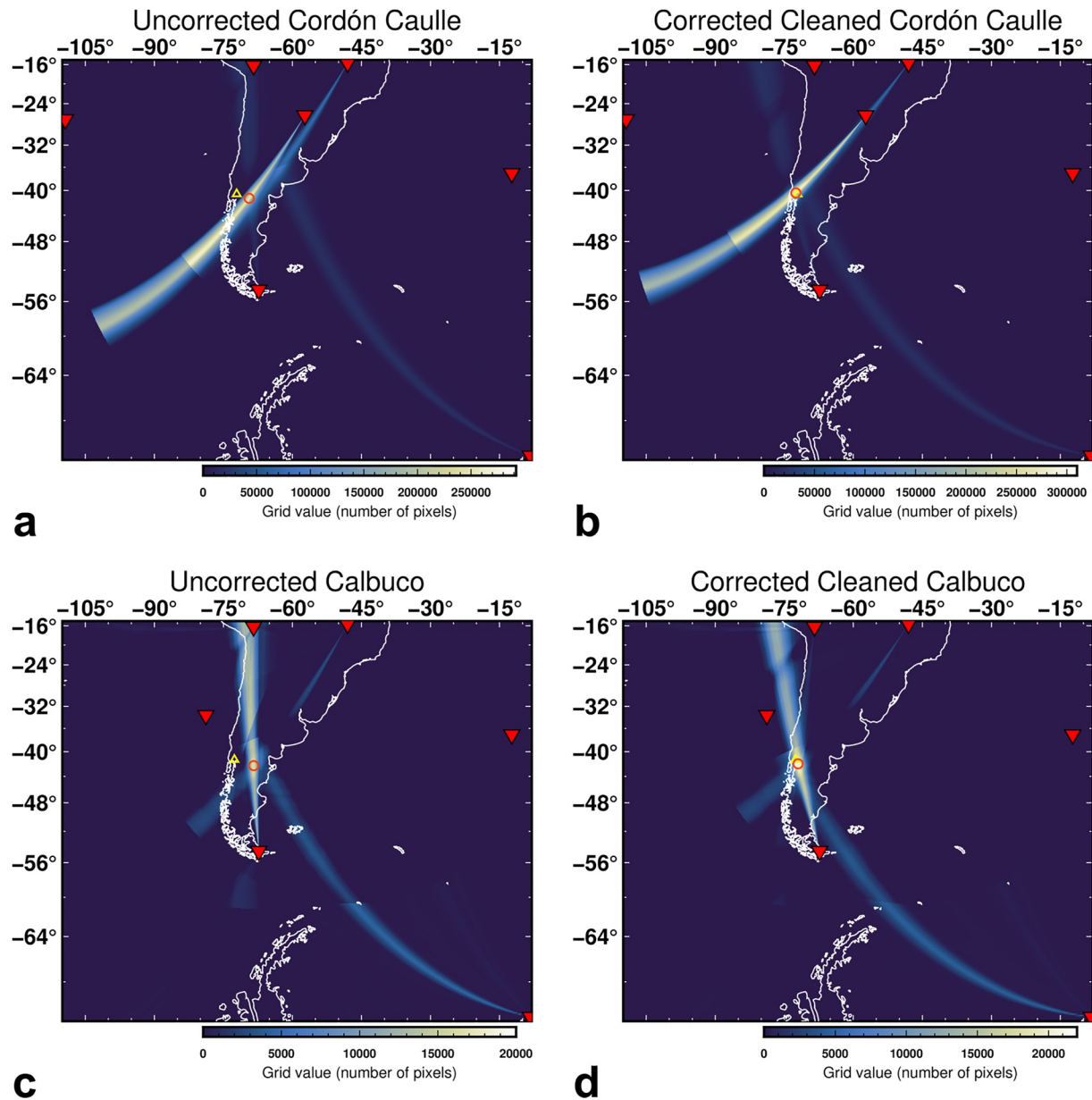


Figure 8. Left (a and c): uncorrected source locations with IMS_vASC for PCCVC and Calbuco volcanoes, with offsets of 242 and 366.4 km, respectively. Right (b and d): best source location results by absolute source location with IMS_vASC for Cordón Caulle and Calbuco volcanoes, with offsets of 38.7 and 90.7 km for the models “Perturbed clim. only strato.” and “Perturbed hybrid strato. and thermo.”, respectively (Figure 7). All source location plots correspond to the cleaned grid, G^c , results (Matoza et al., 2017).

5. Discussion

5.1. Crosswinds and Observed Detections

During the eruptions of Cordón-Caulle (June 2011) and Calbuco (April 2015) strong eastward seasonal winds occurred at stratospheric altitudes, producing similar effects on the infrasound propagation ray paths. West of both volcanoes, the upwind propagation direction of the signals left stations IS13 and IS14 unable to detect the eruptions. At the east, the downwind propagation direction favored long-range propagation that resulted in clear volcanic infrasound at most of the stations. With volcanic infrasound detection frequencies usually lower than 2 Hz, this is an expected effect of the yearly global stratospheric wind circulation patterns (Le Pichon et al., 2009). The observed backazimuth deviations (see Figure 2) follow the patterns of a source that seems to be “pushed” downwind (east, as illustrated in Figure 3b), producing azimuths that are smaller than true (i.e., positive deviation) for stations to the north

Table 1
Summary of IMS_vASC Results

Volcano	Model	Abs. Δs (km)	Near. Δs (km)	Nearest volcano
Cordón Caulle	Uncorrected	242.0	226.3	Crater Basalt Field
	Raw clim., only strato.	326.7	228.8	Laguna Blanca
	Raw clim., strato. and thermo.	54.5	65.8	Osorno
	Pert. clim., only strato.	251.7	228.8	Laguna Blanca
	Pert. clim., strato. and thermo.	38.7	26.1	Carrán-Los Venados
	Hybrid model, only strato.	297.3	228.8	Laguna Blanca
	Hybrid model, strato. and thermo.	59.5	73.2	Mocho-Choshuenco
	Hybrid pert., only strato.	265.6	251.6	Tralihue
	Hybrid pert., strato. and thermo.	184.3	186.1	Sollipulli
Calbuco	Uncorrected	366.4	215.7	Crater Basalt Field
	Raw clim., only strato.	689.8	537.8	Río Murta
	Raw clim., strato. and thermo.	126.7	52.5	Cuernos del Diablo
	Pert. clim., only strato.	872.9	983.7	Viedma
	Pert. clim., strato. and thermo.	93.1	50.8	Yate
	Hybrid model, only strato.	272.8	215.7	Crater Basalt Volcanic Field
	Hybrid model, strato. and thermo.	119.2	62.4	Hornopirén
	Hybrid pert., only strato.	740.0	537.8	Río Murta
	Hybrid pert., strato. and thermo.	90.7	62.4	Hornopirén

Note. “Abs. Δs (km)” refers to the distance between the obtained apparent source location to the true source location for each case. “Near. Δs (km)” refers to the distance between the nearest holocene-active volcano from the apparent location to the true location of the source.

of both sources (e.g., IS08, IS09, and IS41), and larger than true (i.e., negative deviation) for stations to the south (e.g., IS02 and IS27) of the sources (e.g., Evers & Haak, 2005; Matoza et al., 2018; Matoza, Le Pichon, et al., 2011).

5.2. Predicted Backazimuth Deviations

We see a general agreement between the predicted backazimuth deviations (Figure 6) and the observed backazimuth deviations (Figure 2b). The deviation magnitudes correlate with the crosswind strength along the propagation path of each profile. Stations south from both volcanoes show generally higher deviations than stations at the north, as the zonal winds were stronger at mid-to-high latitudes (see Figures S6 and S7 in Supporting Information S1). High deviations from arrivals that are only thermospheric are associated with near-north or near-south profiles (IS08 and IS02, respectively). High deviations where arrivals are mostly stratospheric are the product of strong crosswinds with an along-path component that increase the effective sound propagation of the signals (e.g., IS27, IS41, and IS09). Low deviations with stratospheric and thermospheric arrivals are present only for IS49, located almost downwind from both volcanoes with a strong favorable stratospheric wind jet (see Figures S2–S5 in Supporting Information S1). Except for IS49, the farthest station considered (~5,000 km) with a subsequent high attenuation propagation, all detecting stations had observations with similar backazimuth deviations than our predictions (see Figure 6).

5.2.1. Thermospheric Arrivals

In cases when both “strato.” and “strato. and thermo.” models have associated backazimuth deviations, their values are similar (e.g., IS09, IS27, IS41, and IS49). The slightly higher average backazimuth deviation estimation for the “strato. and thermo.” cases (~1°) is produced by the higher deviations thermospheric arrivals have in our models. The agreement between “strato.” and “strato. and thermo.” values, suggests that in cases where no stratospheric arrivals were found (e.g., stations IS02 and IS08 in Figure 6), thermospheric arrivals aid with modeling crosswind effects. This is also reinforced by the significant mislocation reduction obtained when applying corrections derived from “strato. and thermo.” models (see Figure 7). Despite thermospheric

infrasound observations being less feasible and usually not considered in most studies due to their high upper atmosphere absorption (Sutherland & Bass, 2004), our models indicate thermospheric arrivals could explain observations at stations with high crosswinds effects (e.g., IS02 and IS08). Thermospheric paths have been interpreted before for infrasound recorded at IS22, New Caledonia for signals from Lopevi volcano in Vanuatu at a range of ~650 km (Le Pichon, Blanc, Drob, et al., 2005), at IS19 for signals from Nabro volcano at a range of 264 km (Fee et al., 2013), at the LITE array for signals from Tungurahua at a range of 251 km (J. D. Assink et al., 2012), and discussed as a possibility for Calbuco (2015) (Matoza et al., 2018). The long-range propagation for the considered stations (>1,500 km) and possible thermospheric path for 2015 Calbuco and 2011 Cordon Caulle warrants further investigation.

5.2.2. Tropospheric Arrivals

The existence of tropospheric turning heights ($\sim < 25$ km) in the hybrid model case from Calbuco to IS02 (see Figure S10 in Supporting Information S1) suggests considering a third category of arrivals in the search process. However, the modeled backazimuth deviations for tropospheric arrivals are much smaller than the “strato. and thermo.” cases ($\sim 3^\circ$ vs. $\sim 10^\circ$) and we did not find many observations with such deviations values (see Figure S12a in Supporting Information S1). Additionally, tropospheric wind jets tend to have shorter time spans and cover smaller regions (Drob et al., 2003), which are features that will be smoothed out by the empirical climatologies (e.g., Le Pichon, Blanc, & Drob, 2005).

5.2.3. Perturbed Cases

The climatological perturbed models have higher deviation values, generally better matching the observed mean and median observed of the detections. For some of the hybrid results (e.g., IS09 and IS41 for Cordón Caulle), it seems that the Gaussian perturbation introduces an overcorrection that results in an increased overall mislocation (see Figure 7 for Cordón Caulle hybrid “strato. and thermo.” cases). When perturbing the empirical climatologies, on the other hand, the source mislocations always reduce for “strato. and thermo.” cases, supporting the idea of using a simple Gaussian perturbation to enhance the stratospheric duct effects.

5.3. Source Locations

The completeness of the IMS network is critical for source location purposes (Le Pichon et al., 2009) and this manifests when comparing the Cordón Caulle and Calbuco results. The lack of IS41 detections on April 2015 produces a basal (uncorrected) source mislocation increment of ~120 km for Calbuco when compared to Cordón Caulle, setting a limit on the location accuracy for Calbuco eruption that is clear across our source location results (Figures 7 and 8). Another major factor in the increase or reduction of the source mislocation was the existence of correction values for the most relevant detecting stations. From Figure 8 it is clear that the mislocation increases when applying corrections to a very limited number of stations. For example, the case of perturbed climatologies with only stratospheric arrivals does not find deviations for IS02 and IS08, which are determinant to constrain the source longitude, resulting in a cross-bearing maximum that is actually much farther from the uncorrected location (see Figure 7; also see Figures S13–S18 in Supporting Information S1). The low number of predictions for “only strato.” cases shows that the iterative search of arrivals is less effective in converging toward the target station location when using only rays with stratospheric turning heights. We think this could be partially tackled by fine-tuning the iteration launch parameters case by case (e.g., changing the launch azimuths for IS02 or IS08), but in this study we kept the same modeling parameters across all cases for consistency (see Text S1 in Supporting Information S1 for more insights of possible improvements in the search algorithm). Nevertheless, the “strato. and thermo.” cases are very effective in reducing the source mislocation as they provide robust deviation estimations for nearly all stations. This suggests that when using a cross-bearings approach such as IMS_vASC, the corrections should only be applied if a minimum number of detecting stations is involved. In this study, whenever the stations IS02, IS08, IS09, IS27, and IS41 had associated correction values we obtained a significant source mislocation reduction (Figure 7 and Table 1).

Our results indicate that our automatic climatology-based methodology could provide rapid and robust predictions of the backazimuth deviation for similar source location cases. Applications of this methodology extend to the case of using yearly predictions of backazimuth deviation behavior to discriminate volcanic infrasound from clutter (De Negri et al., 2022). Upon further testing and performance tuning (see Text S1 in Supporting Information S1) we think the method has good potential to be used for studies that involve large temporal and spacial data sets, and also near real-time infrasound location systems.

5.4. Blind Search

We expect that our approach should generally limit the contribution of clutter (Matoza et al., 2013) and reduce the rate of false associations and detections by limiting the number and spatial distribution of trial source nodes that can be linked for each station (Figure 3). In this sense, a priori trial source nodes could be mapped to specific backazimuth deviation values, or rejected as implausible trial source locations, depending on the time of the year and receiver location, generally improving source location and association capabilities. The present study investigates the degree of mislocation reduction for known sources and the overall feasibility of the method (Figure 3). Further implementation and integration into a blind search algorithm (Matoza et al., 2017) could be explored in future work.

6. Conclusions

We introduce a method for rapid first-order estimates of infrasonic backazimuth deviation to improve source-location procedures for a grid of trial source-receiver pairs based on empirical climatologies (HWM14/NRLMSIS2.0) and 3-D ray tracing (GeoAc/InfraGA). The use of empirical climatologies enables the estimates to be pre-computed a priori, rendering the method suitable for real-time applications or systematic analyses of large infrasound data archives. Our approach prioritizes rapid and efficient computation speed over atmospheric and infrasound propagation realism. We employ a simple Gaussian wind jet profile perturbation parameterization to enhance marginal ducting conditions within reasonable bounds and thus compensate for the missing information on fine-scale atmospheric structure in the empirical climatologies. We evaluate our approach based on infrasound source location case studies for two volcanic eruptions in Chile recorded by the IMS: the 2011 eruption of Puyehue-Cordón Caulle volcanic complex and the 2015 eruption of Calbuco. Overall, we find that our approach using perturbed empirical climatologies provides an improvement in source location compared to having no backazimuth deviation correction. For the two case studies considered, the results using climatological models compare well with results based on realistic hybrid atmospheric specifications (ECMWF ERA 5 reanalysis below ~80 km combined with climatologies for higher altitudes). Thus, a practical workflow for real-time monitoring applications can combine empirical climatologies for rapid first-order source-location estimates, followed later by refined source-location estimates using hybrid atmospheric specifications once available. We emphasize that in this study we used the known volcanic source locations a priori to compute the backazimuth deviations at the stations, with the goal of evaluating the overall approach with climatologies. Extension of the method to a blind search process with a grid of trial source nodes represents future work.

Data Availability Statement

- All IMS data are available for scientific studies through the CTBTO vDEC platform (<https://www.ctbto.org/specials/vdec/>).
- For the hybrid models we used the CDS API tools freely provided by European Centre for Medium-Range Weather Forecasts (ECMWF) to obtain the necessary ERA5 reanalysis profiles, publicly available for academic research (<https://confluence.ecmwf.int/display/CKB/How+to+download+ERA5>).
- The climatology (HWM/MSISE) model codes are available from Drob et al. (2015) and Emmert et al. (2020), respectively.
- The code for this project is available for research purposes in the GitHub repository <https://github.com/rodrum/arcade> along with instructions and examples. The code release used for this work can be accessed through Zenodo in <https://doi.org/10.5281/zenodo.7643898> (De Negri, 2023).

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