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Acoustic Sensing of Glacial Discharge in Greenland

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Key Points:

- Sound propagating in the atmosphere can be used to estimate proglacial discharge
- Audible frequencies between 50 and 375 Hz are most informative at a short range
- A simple microphone is a promising and economical tool for glacial hydrology

Supporting Information:

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

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Abstract

The accessibility and simplicity of monitoring instruments and processing methods are crucial for environmental monitoring worldwide. There is growing evidence that proglacial discharge may be observed by listening to the glacier terminus using sophisticated tools, such as the micro-barometer arrays that are used for nuclear-test monitoring and the fiber-optic technologies that are becoming increasingly used in geophysics. However, the prohibitive cost, instrumental complexity, overwhelming data volumes, and computational demands of these approaches mean that only the wealthiest countries can afford such technologies. We employ an intentionally inexpensive approach to monitor proglacial discharge by recording the audible sound that is generated near the glacier terminus, and we show that a simple microphone can tell us how much water is discharged by a glacier. This study demonstrates that sound can provide essential information on runoff and therefore contribute to environmental assessments of glaciers and disaster risk reduction of glacial flood events.

Plain Language Summary

Glacier monitoring is essential for sea-level-rise forecasting, water management, and providing an early warning of potential glacial flooding; however, the necessary monitoring data are currently scarce and often difficult to collect. Recent studies on turbulent streams and melting glaciers have suggested that the acoustic signals that are generated from these systems can serve as a proxy for high-resolution discharge monitoring. We collected acoustic and runoff records from the terminus of Qaanaaq Glacier, Greenland, to examine this sound–glacier discharge relationship. We demonstrate that the proglacial discharge can be estimated from the audible sound that is generated near the terminus, without the need for expensive monitoring equipment and sophisticated machine-learning analysis. We identify that the 50–375 Hz frequency band may serve as the most efficient proxy and associate the recorded sound (and previously reported persistent infrasound) with the turbulent proglacial stream. Our non-invasive approach is ~100 times cheaper than current fiber-optic technology, can easily be deployed at any safe location near the terminus, and requires only basic processing of the recorded signal, thereby making it a safe, affordable, and effective approach to monitoring discharge. It may also be a viable tool for long-term glacier monitoring, particularly where glacial flooding events pose a risk.

1. Introduction

It was discovered in 2022 that the world's northernmost infrasound array (I18Dk; the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), monitoring station in Northwest Greenland) was recording coherent infrasonic signals that peaked during summer (Evers et al., 2022). Most of this inaudible energy (1–5 Hz) had been propagating from the direction of the nearest land-terminating glacier for the past 18 years (Figure 1a). Similar signals have been recorded in the same region using a temporary infrasound array, with these observations linked to another land-terminating glacier (Podolskiy et al., 2017). Both studies noted daily variations in the recorded acoustic signals, and they hypothesized that these signals might be from radiating air-pressure waves that were generated by glacial runoff (Evers et al., 2022; Podolskiy et al., 2017).

Although these previous studies could not distinguish the sources of the low-frequency acoustic signals (<20 Hz) that were recorded a few kilometres from the corresponding glaciers, both suggested that there was potential to monitor runoff remotely via an analysis of these propagating air-pressure waves. There are three additional reasons that have motivated the use of passive acoustic monitoring to monitor glacial discharge.

1. *In situ* streamflow monitoring is a labor-intensive process, thereby highlighting the need for remote monitoring approaches. Acoustics offers one such possibility. However, further investigations are required to assess its feasibility due to a number of poorly understood factors affecting noise, such as air/sediment entrainment, magnitude of water flux, and streambed geometry (Gauvain & Anderson, 2022).

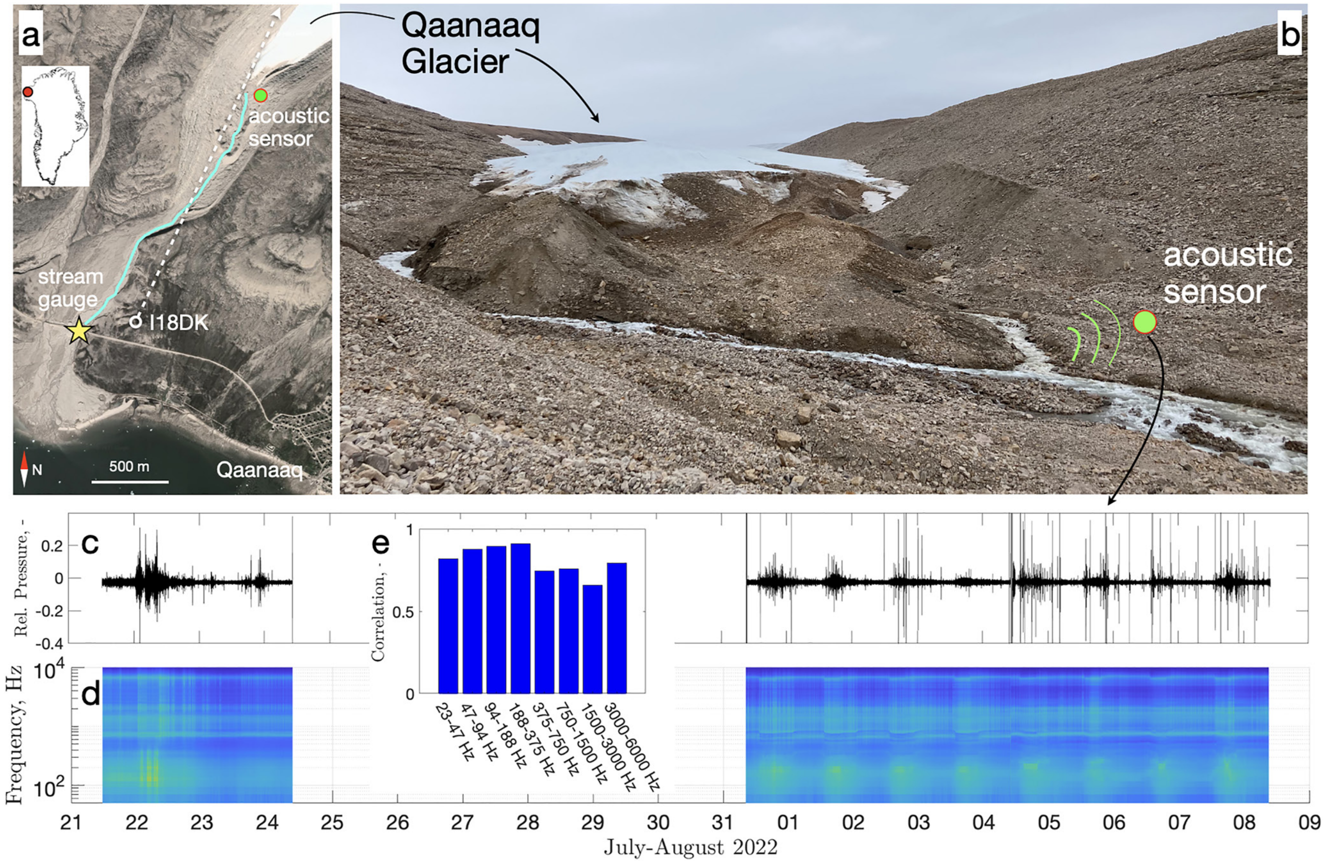

Figure 1. (a) Study site and set-up along the outlet stream (cyan) of Qaanaaq Glacier, Northwest Greenland. The empty circle indicates the center of a microbarometer array (I18Dk) that is operated by Comprehensive Nuclear-Test-Ban Treaty Organization. The back-azimuth from Evers et al. (2022) is plotted as the white arrow and corresponds to the persistent infrasonic energy. Satellite imagery was retrieved on 15 August 2017 (a courtesy of Maxar Technologies/Google Earth). (b) Location of the acoustic sensor next to the outlet stream near Qaanaaq Glacier (Photo: E. A. Podolskiy, 21 July 2022). (c) Overview of the raw acoustic data that were collected by the acoustic sensor (green circle in (a and b)) and (d) their corresponding long-term spectrograms. (e) Correlation between the proglacial discharge measured at the stream gauge (star in (a)) and the median power spectra density noise levels, as a function of frequency band. The data in (c and d) are shown in LT (UTC–02:00).

2. In Greenland, glacier monitoring is particularly important for global sea-level rise projections, since glacial discharge is expected to increase owing to intensifying ice-sheet ablation in the future. However, such monitoring is virtually nonexistent, with only a few sites possessing hydrographs to monitor meltwater discharge (Esenther et al., 2022; Kondo et al., 2021; Mankoff et al., 2020).
3. Environmental seismo-acoustic monitoring is becoming more widespread and can now sample across up to 20 octaves thanks to fiber-optic technology (Lindsey & Martin, 2021; Paitz et al., 2020). However, although there has been a recent surge in the number of glacier-related studies using seismometers (Podolskiy & Walter, 2016) and fibers (Booth et al., 2020; Hudson et al., 2021; Manos et al., 2022; Walter et al., 2020), the number of attempts to interpret the audible sounds of glaciers is almost nonexistent (Podolskiy, 2020).

Here, we hypothesize that the diurnal variations in the audible roar of a proglacial stream should be recognizable and proportional to proglacial discharge based on recent findings and advances in infrasonic and fiber-optic reports (Evers et al., 2022; Manos et al., 2022; Podolskiy et al., 2017). We present the first near-source study of this acoustic phenomenon in Greenland, which reveals that the ambient-noise level scales with proglacial discharge in the upper seismic and lower acoustic frequency bands (50–375 Hz). Passive acoustic sensing can therefore be used to remotely and continuously measure proglacial discharge at a high temporal resolution. Furthermore, the presented approach is more accessible to the global research community, as audio recording is ~100 times cheaper than fiber-optic technology.

2. Site and Methods

The study site was located in the drainage basin of Qaanaaq Glacier, near the settlement of Qaanaaq (77°28'N 69°14'W) in Northwest Greenland (Figure 1a). This glacier has been the subject of previous investigations (Sugiyama et al., 2014; Tsutaki et al., 2017) and was visited in July–August 2022 to acquire comprehensive glaciological observations, including the acoustic and glacier runoff measurements presented in this paper.

The ambient soundscape was recorded using a Song Meter Micro recorder (Wildlife Acoustics; Maynard, USA), which provides 16-bit resolution, that was set to a 24 kHz sampling rate (i.e., Nyquist frequency of 12 kHz). The Song Meter Micro can run for approximately 3 days on three AA Alkaline batteries and saves 1-hr-long single-channel wav files on a micro SD card. It can also be operated remotely via Bluetooth using a smartphone. The recorder self-noise and sensitivity are relatively flat between 0.5 and 14 kHz, excluding an increased sensitivity at ~6 kHz. The collected audio data were proportional to acoustic pressure with an arbitrary reference. Detailed technical specifications of the Song Meter Micro recorder are available at WildlifeAcoustics (2023).

The acoustic sensor was deployed near the terminus of Qaanaaq Glacier (77°29.34'N 69°15.46'W, 195 m above sea level; Figure 1b). To protect the sensor from the elements (rain and wind), it was placed under a rock, and we acknowledge that this might lead to some obstruction of sound propagation. The sensor recorded the ambient soundscape for approximately 11 days in total (21–24 July and 31 July–8 August 2022). It was visited every 3 days for battery replacement (with the exception of a week-long gap due to our inability to visit the site).

The proglacial discharge was estimated from the automatic water-depth measurements that were taken every 10 min (17 July–28 August 2022) at the intersection of the proglacial stream and the road between Qaanaaq and the airport (Figure 1a), following the methodology of Kondo et al. (2021). This monitoring location is important from a practical perspective due to overtopping and erosion events (Kondo et al., 2021), which can either destroy the road or impede the use of any sensors in the stream. Flow-speed and river-bed profiles were measured across the stream 28 times during the survey period to establish a relationship between the water level and discharge (Kondo et al., 2021). The mean slope gradient between the stream gauge and the glacier terminus was ~7°.

We analyzed the acoustic data by first constructing long-term spectrograms (LTSs) to extract the median power spectra densities for different frequency bands, following Guan et al. (2015); Merchant et al. (2015). Each LTS was computed with a 10 s time resolution using a 1024-sample-long fast Fourier transform window size that spanned the 20–11,000 Hz frequency range. All of the results were processed in local time (LT; UTC–02:00). The discharge was then cross-correlated with the noise using one-octave-wide frequency bands (between 20 and 6,000 Hz) to identify the frequency band that best captured the acoustic signal that was generated by the proglacial stream.

3. Results

The 265 hr (45 Gb) of continuous raw audio data that were acquired near the terminus of Qaanaaq Glacier and their corresponding LTSs are shown in Figures 1c and 1d, respectively. The highest correlation between proglacial discharge and the median spectral power of the audio data set is observed in the 50–375 Hz frequency range (Figure 1e). Figure 2 demonstrates the quality of this strong correlation, whereby the acoustic noise level clearly mimics the temporal variations in proglacial discharge (mean $\pm$ 1σ value of 1.5 $\pm$ 0.9 m^3 s^{-1}) during the entire observation period. We note the following three main features from the noise–discharge plot (Figure 2).

1. There is generally a strong diurnal pattern in the acoustic noise level, with highest and lowest noise levels occurring in the evening (17:50 $\pm$ 44 min LT) and morning (08:56 $\pm$ 46 min LT), respectively. The strongest disruption to this pattern was observed on 22 July, when both the maximum noise level and discharge occurred in the morning (05:30–06:30) due to rain.
2. Proglacial discharge lags the acoustic noise by 50 min (based on a cross-correlation of the overlapping time segments, after resampling both datasets to a common timeframe and de-trending). This result holds for all of the frequency bands with the highest correlation (i.e., <375 Hz, Figure 3).
3. The ambient-noise level rises more steeply than it falls, which is also observed in the proglacial discharge data.

We confirmed that there was a distinct audible difference in the evening and morning noise levels from the proglacial stream (Audios S1 and S2). The ambient sound could be described as a continuous hum of roaring

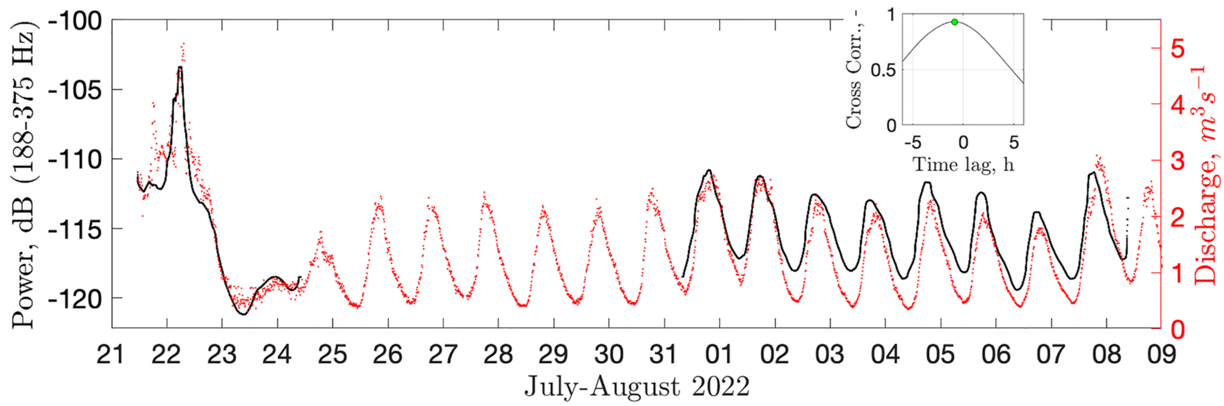

Figure 2. Comparison of the average power spectral level for the 188–375 Hz frequency range (black) near the terminus of Qaanaaq Glacier and the measured proglacial discharge (red). The acoustic signal (dB rel. to arbitrary reference) was smoothed using a median filter with a 5 hr sliding window. All of the data are presented in LT. A correlation coefficient of 0.91 (coefficient of determination $R^2 = 0.83$) is obtained for these data sets. The inset plot shows the cross-correlation results, whereby the maximum correlation is obtained when the discharge lags the noise by ~50 min.

water. Short-duration (~0.2 s) transient sounds that corresponded to entrained boulders hitting discontinuities along the stream bed were occasionally heard within this hum (Audio S3); detailed waveforms and a spectral view of a boulder's passage are shown in Figure 3.

4. Discussion

Proglacial discharge is controlled primarily by surface processes that generate supraglacial runoff and potentially by a minor contribution from subglacial hydrology (Esenther et al., 2022; Kondo et al., 2021). The overall response time of the drainage basin to solar radiation and positive temperature typically yields maximum runoff in the evening. However, liquid precipitation, wind, and anomalous temperatures may disrupt this diurnal variation. All of these processes drive proglacial discharge, which generates an audible sound.

There are no recognizable supraglacial meltwater streams, moulins, or waterfalls near the terminus of Qaanaaq Glacier, where the acoustic sensor was positioned. Therefore, these features are not acoustic sources in the recorded audio data (Manos et al., 2022; Podolskiy, 2020; Podolskiy & Walter, 2016). Water instead emerges from cavities at both lateral sides of the glacier trunk a few tens to hundreds of meters upstream. It flows down a sloping terrain till convergence of two streams in front of the terminus (Figure 1b), leading to some undercutting

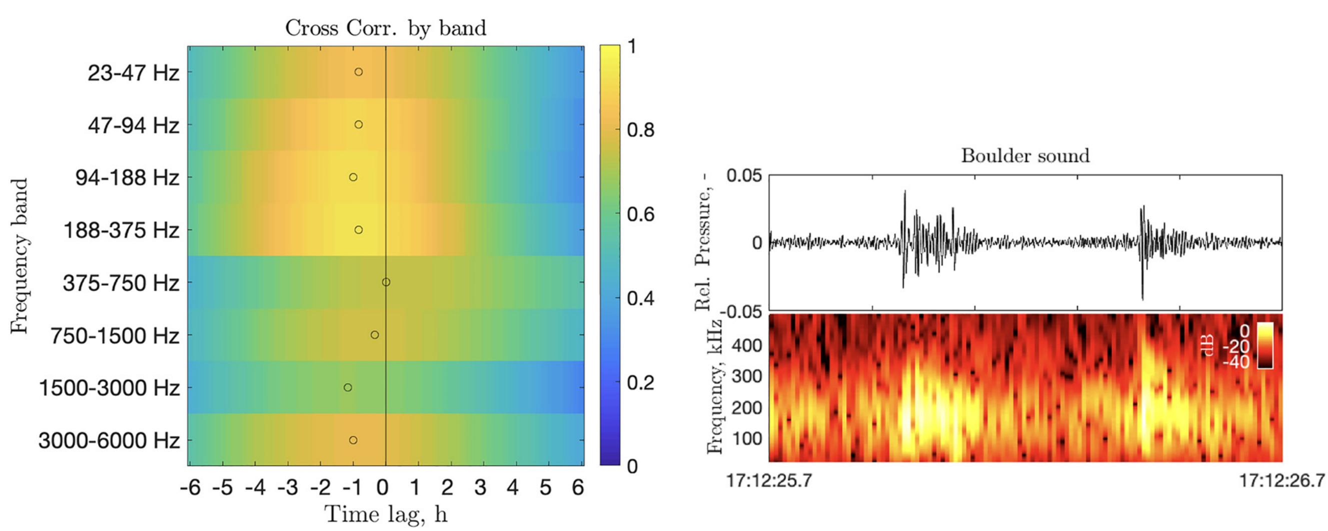

Figure 3. (Left) Cross-correlation between proglacial discharge and noise as a function of a chosen frequency band. Circles indicate the time lag at the peak correlation value (Right) Bandpass-filtered (20–500 Hz) waveforms and spectrogram of boulders hitting the stream bed (31 July 2022). Data are presented in LT.

of lateral ice. This configuration reduces the number of potential acoustic sources to a steep streamflow over rocks, which generates the audible roar that is actually heard and recorded in this study.

The stream sound is an audible mix of continuous white-water hum and discrete bedload transport events. Separating such covarying sound sources currently presents an outstanding challenge in fluvial research (Roth et al., 2022). The above-mentioned transient nature of bedload transport (Figure 3) may be elusive, as multiple weaker events could be hidden in the signal owing to a low signal-to-noise ratio, while still shaping the spectral signals. For example, the spectra of boulder sounds (50–400 Hz) span the same frequency band that yields the highest correlation to proglacial discharge (Figure 1e).

However, it is important to recall that: (a) we are looking for a broadband acoustic source, (b) persistent infrasound (Evers et al., 2022) is unlikely to be produced by bedload transport (to our knowledge, there are no reports of infrasound generation by such sediment transport process - contrary to debris flows (Belli et al., 2022)), and (c) a previous study suggested that supraglacial meltwater is the most likely source of 100–500 Hz vibrations (Manos et al., 2022). Therefore, we suggest that turbulent fluvial flow is the main cause of the recorded audible sound, as this type of acoustic signal has been linked to turbulent flow in different fluvial settings (Gauvain & Anderson, 2022). We applied bootstrapping to a linear regression model to estimate the predictive capability of using audible sounds as a proxy for proglacial discharge and obtained a mean absolute error of 0.4 ± 0.01 m^3 s^{-1} from 1,000 simulations. This level of uncertainty is the same order of magnitude as that achieved by the more mathematically complicated models of Manos et al. (2022).

The most likely cause of the time lag between the proglacial discharge and noise data (Figures 2 and 3), is the distance between the terminus and stream gauge. A water flow rate of ~0.7 m s^{-1} would be required to travel the ~2,157 m along the meandering proglacial stream to the stream gauge in 50 min. This is a reasonable flow rate because the median current in the center of the stream was 0.78 m s^{-1} ($n = 31$, 20 July–12 August 2022). Such a lag due to the distance between the stream gauge and noise monitoring site should be taken into account in comparable seismic and infrasound studies (Preiswerk, 2018), as well as the physical constraints that are placed on machine-learning techniques that correlate hydrograph data to remote acoustic receivers (Manos et al., 2022).

Finally, we acknowledge that the sound–discharge relationships may be complex, as suggested by LTSs (Figure 1e). For example, some subglacial cavities may become over-pressurized with water at high discharge rates, thereby producing peculiar acoustic phenomena with step-like shifts in their spectral characteristics. However, the overall good correlation of the sound–discharge relationship suggests that these secondary effects may be negligible. Furthermore, it has been suggested that infrasound can be produced as the discharge exceeds some threshold (Gauvain & Anderson, 2022). Therefore, earlier reports of infrasound events that apparently radiated from the terminus direction (Evers et al., 2022) could be explained solely by turbulent fluvial flow. The outlet stream, which is represented by a long sequence of rapids, flows exactly along the azimuth of the CTBTO array over a distance of at least 800 m. On the one hand, this suggests that glacial discharge is a spectrally broad acoustic phenomenon that is most likely generated by stream-bed discontinuities, which disrupt the laminar flow of the discharge, with minor contributions from acoustic resonators, such as glacial channels, pipes and cavities, and supraglacial streams (Evers et al., 2022; Manos et al., 2022). On the other hand, this suggests that all acoustic power generated by the stream lying along a single azimuth from the infrasound array presumably contributes to its detectability.

5. Concluding Remarks and Outlook

Here we demonstrate the feasibility of employing acoustic sensing as a valuable tool for glacio-hydrological sensing. Although this quasi-point-measurement approach does not provide the high spatial resolution of fiber-optic approaches, its greatest advantages are its affordability and overall simplicity, which include its quick deployment (simply place at a safe location near the glacier terminus) and non-sophisticated signal processing due to the relatively small data volume generated by this single-channel approach. Therefore, we suggest that audible acoustic sensing can serve as a practical tool for monitoring proglacial discharge, with a reduced risk of losing instruments since they are not deployed directly into the proglacial stream. Furthermore, the placement of the acoustic sensor near the glacier terminus, coupled with the acquisition of continuous real-time measurements, provides the opportunity to detect and respond to extreme runoff events, such as glacier lake outburst floods (Eibl et al., 2020), in a more timely manner, thereby mitigating the devastating impact of these glacial flooding events.

Future studies could consider the following topics to ensure efficient acoustic deployments and successful interpretations. (a) Microphones are sensitive to wind, which may have diurnal variations; therefore, it would be helpful to have wind data (measured or modeled) for identifying periods of increased wind strength. (b) Two and more microphones (i.e., an array) might help isolate pressure fluctuations due to wind from acoustic signals based on their back-azimuth and propagation velocity (e.g., the wind is two orders of magnitude slower than acoustic wave). Finally, (c) our results further confirm that measuring over a broad frequency range, from infrasound to acoustic domain, is scientifically fascinating. On the one hand, infrasound monitoring with discrete sensors can be conducted near-source, reducing costs and data volume (Anderson et al., 2017). On the other hand, a combination of discrete observations with sophisticated arrays (Evers et al., 2022) may allow better identification and characterization of sources.

Data Availability Statement

Data are publicly available and enclosed in supporting information (Podolskiy, 2023). Long-term spectrograms were computed using open codes by Guan et al. (2015) (https://github.com/schonkopf/long-term-spectrogram). Audio (Audios S1–S3) files were inspected in publicly available Raven Lite 2.0.0 (Cornell Lab of Ornithology: https://ravensoundsoftware.com/software/raven-lite/).

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