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Un Suono In Estinzione (*USIE*): a STEAM project for capturing and preserving the sounds of glaciers

Abstract: Maggioni S., Astolfi A., Baroni C., Carton A., Casarotto C., Colosio P., Degani A., Ferrari C., Lendvai A., Smiraglia C., Tedesco M. Ranzi R., Un Suono In Estinzione *(USIE): a STEAM project for capturing and preserving the sounds of glaciers.* (IT ISSN 0391-9838, 2024). Glaciers are dynamic systems of snow and ice that accumulate and melt, producing a wide range of sounds associated with morphodynamic and hydrological processes, such as their deformation and movement, melting and refreezing cycles, and ice collapse. The USIE (*Un Suono In Estinzione*) project leverages sound analysis to investigate Alpine glacier evolution and to raise awareness of climate change impacts. Through a multidisciplinary approach, the project aims to advance scientific research in alpine glacier hydrology while creating artistic performances and installations, both relying on the same dataset of recorded sounds. Such an approach can be classified as STEAM, as it integrates Scientific research, Technology, Engineering, Art, and Mathematics, incorporating into the classical STEM aspect, typical of classical hydrological and cryospheric sciences, the perceptual and emotional dimensions typical of sound arts. Between 2021 and 2023, over 14,000 hours of acoustic data were collected on the Adamello Glacier using five bioacoustic recorders, suitable for long-term outdoor deployment, placed in strategic locations, such as crevasses and meltwater streams. For the same years, the spatially distributed energy and mass balance Physically based Distributed Snow Land and Ice Model (PDSLIM) model has been used to compute surface melting and runoff at the sound recorders' locations. In order to capture the daily variability of surface melting, the model requires hourly temporal resolution meteorological input data. Here, we show how acoustic monitoring can be used for the calibration and validation of the surface melting model. We show how the sound pressure daily variability reveals insights about timing and amplitude of snow and ice melting cycles and the hydrological response of the glacier, highlighting seasonal and daily patterns. Through this innovative approach, we investigate the potential of acoustics as a complementary tool for advancing cryospheric and hydrological science while emotionally communicating the critical conditions of alpine glaciers.

Key words: USIE, Adamello Glacier, sounds, ice melt, art, PDSLIM Model, climate change.

Riassunto: Maggioni S., Astolfi A., Baroni C., Carton A., Casarotto C., Colosio P., Degani A., Ferrari C., Lendvai A., Smiraglia C., Tedesco M. Ranzi R., Un Suono In Estinzione *(USIE): un progetto STEAM per catturare e preservare i suoni dei ghiacciai.* (IT ISSN 0391-9838, 2023). I ghiacciai sono sistemi dinamici di neve e ghiaccio che si accumulano e fondono, producendo un'ampia gamma di suoni associati a processi morfodinamici e idrologici, come la loro deformazione e movimento, i cicli di fusione e rigelo e il collasso del ghiaccio. Il progetto USIE (*Un Suono In Estinzione*) sfrutta l'analisi del suono per studiare l'evoluzione dei ghiacciai alpini e per aumentare la consapevolezza del pubblico sugli impatti dei cambiamenti climatici. Attraverso un approccio multidisciplinare, il progetto mira a far progredire la ricerca scientifica sull'idrologia, l'idraulica e la dinamica dei ghiacciai alpini, creando al contempo performance e installazioni artistiche, basate sui suoni registrati. Tale approccio può essere classificato come STEAM, in quanto integra ricerca scientifica, tecnologia, ingegneria, arte e matematica, incorporando nell'aspetto STEM tradizionale, tipico delle scienze geomorfologiche e idrologiche, le dimensioni percettive ed emozionali tipiche delle arti sonore. Tra il 2021 e il 2023, sono state raccolte oltre 14.000 ore di dati acustici sul ghiacciaio dell'Adamello utilizzando cinque registratori bioacustici, adatti all'impiego all'aperto a lungo termine, posizionati in punti strategici, come crepacci, inghiottitoi, cascate di fusione. Negli stessi anni, il modello Physically based Distributed Snow Land and Ice Model (PDSLIM) di bilancio di energia e massa distribuito

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spazialmente è stato utilizzato per calcolare la fusione superficiale e il deflusso in corrispondenza delle posizioni dei registratori sonori. Per catturare la variabilità oraria della fusione superficiale, il modello richiede dati meteorologici con risoluzione temporale oraria. In questo articolo, mostriamo come il monitoraggio acustico possa essere utilizzato per la validazione del modello di fusione e deflusso. Mostriamo come la variabilità giornaliera della pressione sonora fornisca informazioni sulla tempistica e intensità dei cicli di fusione di neve e ghiaccio e sulla risposta idrologica del ghiacciaio, evidenziandone gli andamenti stagionali e giornalieri. Attraverso questo approccio innovativo, indaghiamo il potenziale dell'acustica come strumento complementare per il progresso della scienza criosferica e idrologica, comunicando al contempo in modo emozionale le condizioni critiche dei ghiacciai alpini.

Termini chiave: USIE, Ghiacciaio dell'Adamello, suoni, fusione glaciale, arte, Modello PDSLIM, cambiamento climatico.

INTRODUCTION

Studying the effects of ongoing climate change on the cryosphere, in particular glaciers and ice sheets, is crucial to understanding the future of the Earth's climate, sea level rise and freshwater resources availability. The retreat of continental glaciers, of Greenland and Antarctica ice sheets and the shrinking of Arctic sea ice in the last decades are the most clear evidence of the effect of global warming on the cryosphere on our entire planet (Zemp *et al*., 2019). In order to reach consensus and communicate beyond the scientific community the urgency of mitigation and adaptation measures to face these changes it is important to touch the emotions of people. Arts can be an effective medium to communicate scientific results. For this reason, the sound artist Sergio Maggioni, living in Valle Camonica, at the foothill of the Adamello mountains group in the Rhaethian Alps, with the largest Italian glacier, contacted in 2020 scientists who investigated the dynamics of this glacier from a scientific point of view suggesting an alliance between science and art to raise the awareness of people on the effects of global warming. This proposal was well acknowledged by a group of researchers and glaciologists also because it offered the opportunity to test methods alternative to the traditional ones adopted in glaciology for monitoring the dynamics of glaciers. Traditional methods using satellites, models or ground observations can be complemented by innovative techniques that make use of sound waves, rather than electromagnetic or topographic ones. From seismic waves that reveal the internal structure and basal conditions of glaciers, to acoustic emissions that shed light on ice fracturing and movement, and ultrasound techniques that uncover fine-scale features, sound-based methods offer specific insights into ice behavior. Seismic waves, for example generated by ice sliding or icebergs calving, have been previously studied in glaciology. Murray *et al.* (2000) used seismic reflection to investigate the ice-bed interface of a polythermal glacier, revealing complex interactions between ice and subglacial water. Baker *et al.* (2003) utilized seismic refraction (i.e., the bending of seismic waves as they pass through different materials) to measure the thickness of Alaska's glaciers, providing fundamental data for understanding glacier dynamics and potential responses to climate change. Acoustic emissions in glaciers – i.e. the high-frequency waves produced by the rapid release of energy from localized sources within a material such as the fracturing of ice or the movement of ice over bedrock – are recorded by placing geophones on the surface of glaciers. For instance, Röthlisberger (1972) investigated the acoustic emissions from glacier crevassing, finding that the frequency and intensity of these sounds correlate with the rate of crevasse formation. More recently, Nanni *et al.* (2020) investigated temporal variations in subglacial channels beneath Argentière Glacier (French Alps) and their relationship to glacier dynamics. The study leveraged two years of seismic data collected on the glacier, combined with in-situ measurements of basal sliding speed and water discharge, to investigate the physical processes governing subglacial channel dynamics. Glowacki and Deane (2020) used underwater acoustic monitoring to quantify iceberg calving fluxes from Hansbreen Glacier (Svalbard). By combining passive acoustic recordings with time-lapse photography, they analyzed the relationship between the kinetic energy of falling icebergs and the acoustic energy generated upon impact. Passive seismic monitoring involves recording the natural seismic activity generated by glaciers themselves, such as icequakes (i.e., small earthquakes generated by the fracturing of ice) and the movement of ice masses. By analyzing the location, frequency, and magnitude of icequakes, researchers can infer the stress and strain conditions within the glacier. For example, Podolskiy and Walter (2016) studied icequakes in the Swiss Alps to investigate the processes leading to the breaking off of large chunks of ice from the glacier front. Similarly, Hudson *et al.* (2020) used icequakes to provide geophysical observations useful for a better understanding of the physics of glacial sliding. Walter *et al.* (2008) used passive seismic data to identify periods of increased basal sliding in the Gorner Glacier, Switzerland, correlating these with seasonal meltwater input. Ultrasound waves are an effective tool for probing the internal structure of glacier ice, providing detailed insights into its microstructural features. This technique is particularly valuable for examining fine-scale characteristics such as the distribution and size of air bubbles, ice crystals, and impurities. Hellmann *et al.* (2021) measured acoustic velocities in ice core samples from Rhone Glacier using ultrasonic P waves to study crystal orientation fabric, revealing variations in crystal size and orientation that provide clues about past climate conditions. Integrating sound-based methods with other observational techniques, such as satellite remote sensing or in-situ observations, can provide a more comprehensive understanding of glacier dynamics. Combining these approaches allows for cross-validation of data and more robust interpretations.

The use of sound records for hydrological measurements is becoming an innovative technique, for instance in measuring sediment transport. Bonfrisco *et al.*, (2025) collected measurements of bedload discharge using eight geophone plates in the glacier-fed Sulden/Solda River (Eastern Italian Alps) from 2014 to 2020.

However, the collection and sound pressure level signals at different frequencies in the body of glaciers, as crevasses and moulines and at the glacier's outlet stream for 'measuring' melt flow intensity and timing is quite novel (Podolskiy *et al.*, 2023) but it is not a standard practice in glaciology, to the knowledge of the authors. For this reason, we present in this paper the preliminary results, partially presented at EGU25 conference (Ranzi *et al.*, 2025), of the analysis of some samples of the sound data collected during the field campaigns conducted on the Adamello Glacier, in summer 2021 and 2022 with the objective of showing the potential of using acoustic recordings for verifying the simulations glacier's runoff from the Physically based Distributed Snow Land and Ice Model (PDSLIM), a distributed energy and mass balance model (Ranzi *et al.*, 2010; Grossi *et al.*, 2013; Liaqat and Ranzi, 2024). After the description of the STEAM (Science, Technology, Engineering, Arts and Mathematics) project *Un Suono In Estinzione*, a classification of the sound types, source and characteristics is presented. In the following sections the study area and the field campaigns are described. The comparison of the output of the hydro-glaciological model PDSLIM with some of the sound records is finally presented and discussed.

THE *UN SUONO IN ESTINZIONE* PROJECT

Un Suono In Estinzione (USIE described at its official website unsuonoinestinzione.eu) is an experimental art and research project aimed at monitoring and raising awareness of the implications of climate change on glaciers through the analysis of sound, expressed in educational, artistic and scientific activities. The project was born in 2020 from an idea by the researcher and sound artist Sergio Maggioni, aka NEUNAU, around whom a team of professionals from different fields, scientific, artistic and communication, was created in a short time. In the last three years USIE experimented with a new methodology for understanding climate changes on the Adamello Glacier which focuses on the analysis of sound phenomenologies related to temperatures. The development of a custom software created by the project team allowed the analysis of about 15,000 hours of field recording data throughout 3 years of expeditions, providing scientific and artistic significance to the unique dataset. In particular, the englacial and epiglacial sounds recorded allow to precisely identify the time cycle and intensity of the melting on the surface, and the delayed outflow of the subglacial stream. This information, which is difficult to obtain with more traditional instrumentation, is peculiar in order to verify the hypotheses and parameters of the mathematical models that predict the evolution of soon-to-be-extinct glaciers, like the Adamello.

The project integrates scientific research, technology, engineering, art, and mathematics (STEAM) to provide a comprehensive and multi-disciplinary perspective. The project is anchored in a rigorous scientific research framework (S), overseen by a committee of glaciology experts, ensuring that sound explorations are grounded in reliable methodologies. The integration of acoustics into glaciological research offers a novel method for understanding the dynamics of ice melting and structural changes, providing data filling the gaps in traditional measurement techniques. Specialized bioacoustic recorders, hydrophones, and geophones are used to capture acoustic phenomena. These technologies (T) enable continuous monitoring of both continuous and intermittent events, enhancing the temporal resolution of glaciological observations. The expeditions include the placement of sensors in locations previously unreached by these instruments. The collected acoustic data is then analyzed using the custom-built sound engineering (E) software, transforming raw recordings into actionable scientific information for glaciological assessments. The core feature of the USIE project is the intersection of science and art (A). Over the years, USIE has been promoted and presented in the form of artistic installations and educational events at renowned festivals and cultural institutions in Europe and Italy. The use of acoustic data in immersive artistic installations highlights the urgency of climate change through an emotional lens. Within these installations, the scientific data collected comes to life, creating an engaging perceptual and emotional dimension that offers a unique perspective on the negative implications and consequences of climate change on fragile ecosystems. By transforming scientific data into art, USIE embraces the potential of an interdisciplinary approach to drive public awareness and inspire action. The data recorded not only advance scientific knowledge but also seek to engage the public on an emotional level through artistic and informative works able to communicate the urgency of the issues associated with climate change in an unconventional format that focuses on sensory engagement. We realized, through the dissemination activities carried out so far, that the sound reaches people's sensitivity in a visceral way, activating a sense of urgency towards this cause. The acoustic dataset is then used in comparison with the simulations of the PDSLIM mathematical and hydro-glaciological model (M), enabling cross-validation and tuning of the model parameters regulating the simulated hydrological response of glacier melting.

THE SOUNDS OF GLACIERS

Glaciers are accumulations of snow and ice, which flow plastically after deforming under their own weight. Strain rate is conditioned by annual mass balance, temperature, water content, and bedrock topography. Alpine mountain glaciers move down the valley following the component of weight force parallel to the slope on which the glaciers rest, being their movement deeply conditioned by ice thickness, glaciological internal structure, basal ice-bedrock interface morphology and temperature, as well as by basal water content. The movement transfers ice from the accumulation basin to the ablation zone and consequently generates sound phenomena dependent on the morphodynamic processes driving: i) ice ductile and brittle deformation (produced by the strain due to the stress induced by glacier movement), ii) melting and refreezing processes, iii) ice fall and collapse.

During its movement, the ice must adapt to the morphology of the substrate on which it rests. This can happen slowly or quickly; in the former case the ice undergoes plastic deformation, while in the latter brittle deformation induces ice cracking and produces crevasses. Ice bodies also undergo differential movements between the glacier bed and the surface, between the lateral margins and the center of the glacier (controlled by flow lines), and between different positions along its longitudinal profile. Therefore, it is evident that sliding velocity is an important element not only in the origin of noises but also in their temporal frequency and time duration. Velocity is an extremely variable factor both at spatial and temporal scale. Glacier sliding is lower near the bedrock and on the valley walls being higher at the ice surface and depending on the thermal state of the basal ice. Today, alpine glaciers are mainly "temperate" or, better, "wet-based" and therefore water is present not only within the glacier but also at its base (apart from perhaps short winter periods): the higher the water content at the glacier bottom, the faster the flow rate of the glacier is.

Sound effects registered on or within a glacier, can originate within the glacier itself, at its base, at its surface, at the frontal and lateral margins, and in surrounding areas (not in direct contact with the ice but in some way connected to it). Additional categories of sounds are not related to ice and can be classified as bioacoustic (including man), landscape sounds and mechanical noises. Given the lack of terminology, table 1 lists noises produced by glacier dynamics and evolution, as well as other categories of noise we identified with our project.

Noises generated by the dynamics of a glacier can be classified on two bases: according to their genesis and according to temporal variability, persistence (occasional, recurrent, persistent), intensity and duration (from seconds to months; table 1). Regarding the noise origin, taking the glacier as the reference element, the generated sounds can be distinguished into "primary" and "induced". The "primary" ones refer to ductile or brittle deformations of the ice mass itself in relation to its flow; the "induced" sounds are produced by the ice transformations or are triggered by its movement. All the noises related to water resulting from ice melting should be associated with the category of "induced" sounds, that should also include noises produced by debris conveyed by ice, falling on the glacier or moving at its margins. Sounds induced by debris falling or moving on the ice are also "induced".

Among the most relevant sound phenomena, the noise produced by waters flowing from the glacier front or moving within the glacial body emerges in terms of both continuity, diffusion and intensity, being the overall expression of glacial dynamics and evolution. For example, the intensity and duration of the sound produced by water released by ice melting to the proglacial stream(s) are primarily a function of the water flow rate, which is, in turn, conditioned by the extent and persistence of ice melting. From this point of view, relevant is the conditioning related to the intensity and persistence of solar radiation, in turn regulated by seasonality and time of the day.

The opening of crevasses generates another relevant primary sound: deep cracks affecting the glaciers surface document brittle deformation induced by ice movement. They form where tensile stress exceeds the tensile strength of the ice. Terminal crevasses can be found at the glacier head, where moving glacier ice detaches from stagnant ice, or firn adhering on the rocky wall (Bergschrund). Most crevasses develop in the accumulation basins (when ice flow accelerates downstream, i.e., where the glacier bed becomes steeper), and in ablation areas under predominantly compressive stress, where ice flow slows down because the glacier bed flattens or rises.

Noise generated by ice cracking and crevasse opening result in short, sharp snapping and roars. The deformation of the ice in its flow or at the confluence of several tongues can generate other sounds. Intense noises are generated by collapses or detachments, which may be of different origin: collapse of seracs, snow bridges, hanging fronts, sinking of ice doline (cauldrons) or subglacial caves, snow- and ice- avalanches, iceberg detachments in glacial marginal lakes, as well as other detachments. Apart from the noise possibly generated by ice flow, most of the other noises are discontinuous with unpredictable intensity and temporal frequency.

Continuous, or at least recordable with hourly durations, are the sounds generated by the circulating waters on, in, at the base, at the forehead and at the margins of a glacier. Obviously, their recording is possible only at temperatures at or above 0°C and their intensity and duration are strongly dependent on seasonality and time of the day. Monitoring the sound of water inside crevasses is also of particular interest because it can reflect the activity of bédière, which are expressions of intense surficial melting. Worthy of note are popping and tweeting produced by air bubbles trapped in the ice and released by ice melting.

Table 1 presents a proposed classification of the sounds that can be heard on a glacier. For each sound, we provide a descriptive label, a sound code useful for cataloguing, and a set of characteristics designed to support the development of a taxonomy of glacier's acoustics.

In particular, we selected the following facets:

- Genesis: indicates the type of source that generates sound;
- Agent: the entity or process responsible for producing the sound;
- Occurrence: how frequently the sound can be heard;
- Subjective Duration: a perceptual description of the duration of the sound event (Fastl and Zwicker, 2007);
- Temporal Variability: indicates whether the sound remains stable over time or changes dynamically (Chen *et al.*, 2024);
- Loudness: perceived loudness of the sound (Fastl and Zwicker, 2007);
- Soundscape Type: describe the origin of the sound in terms of Geophony, Biophony or anthropophony (Truax, 1978);
- Sharpness: description of spectral quality in terms of frequency content (e.g., a sound with a lot of high frequency content is usually perceived as sharp, Fastl and Zwicker, 2007);
- Tonality: if the sound has a clear pitch or an harmonically pleasant content is perceived as tonal. Conversely, an impulsive sound or a noise like sound is perceived as non-tonal (Fastl and Zwicker, 2007);
- Source Recorder: details on the placement of the recording device and the type of transducer used;
- Recording points Adamello Glacier: information on the specific location and microphone used to record the sound on the glacier.

The proposed classification facets are divided in 3 main categories: the source behavior description (occurrence, duration and variability), the acoustic properties (soundscape type, loudness, sharpness and tonality), and the recording conditions (recorder/microphone, location). While not yet validated across different glacial contexts, this classification is a necessary first step in organizing the observed and expected acoustic complexity of the glacial environment. Scientific taxonomies often begin with empirical schemes that are later refined through testing and community consensus. Given the novelty of this research, we believe that there is wide space for improvement and development for the proposed taxonomy.

For space issues in the table's cell, the recording points are coded as follows:

1) Condenser/Surface - 2800 meters in the Mandrone crevasse area;
2) Condenser/Surface - 2600 meters Glacier Front (Lake);
3) Condenser/Surface - 2400 meters Fusion Waterfall;
4) Condenser/Crevasse - 2800 meters in the Mandrone crevasse area;
5) Hydrophone - 2800 meters in the Mandrone crevasse area;
6) Condenser/Moulin - 2800 meters in the Mandrone crevasse area.

In the following, we describe some of the sounds that have been recorded from the point of view of acoustic characteristics and genesis. These sounds can be heard online by playing the videos of the corresponding specific sound uploaded in the open access repository in Supplementary Material and at the link: https://www.unsuonoinestinzione.eu/en/science/egu25-19073.

DISCONTINUOUS SOUNDS

Acoustic Emissions from Air Bubbles Trapped in Ice

The release of air bubbles trapped in the ice, due to pressure variations, generates acoustic emissions of particular interest, which are mainly perceptible near the glacier surface. This phenomenon is most intense during nighttime hours, when the subglacial meltwater flow slows down. Recordings were primarily conducted inside crevasses using condenser microphones and on the glacier surface through hydrophones in direct contact with the ice. The spectral and timbral characteristics of these sounds outline an unexpected soundscape, hardly associated with a glacial environment, and provide an additional analytical tool for studying melt dynamics and the release of gases trapped in the ice.

Internal Dynamic Movement of the Glacier

The internal dynamics of the glacier, driven by structural collapse or mass displacement, generate powerful and distinctive acoustic emissions. These sounds propagate through the ice due to energy transfer resulting from movement or fracturing events. The use of stereophonic recording techniques has enabled the analysis of sound propagation within the glacier, providing insight into its spatial dynamics. This phenomenon was captured using suspended recorders placed within crevasses, as well as hydrophones and geophones, allowing for a comparative analysis of the acoustic signals associated with different types of internal glacier motion.

Glacier Front Collapses

Glacier front collapses are high-intensity acoustic events caused by the collapse of portions of the glacier's front. These sounds are recorded using condenser microphones placed at a short distance from the glacier's front line, typically just a few meters from the detachment zone.

Debris and Rocks

A relevant series of noise is referable to those sounds generated by the collapse of debris or rocks, which are very discontinuous. Among this category of sound, we can indicate those noises produced by:

a) the rubbing and shifting of epiglacial deposits (debris covers) during their transport;
b) the impact of sliding debris from the glacial tongue to the lateral or frontal moraines;
c) debris fall produced by differential ablation from the median moraines;
d) the collapse of part of the inner slope or of individual clasts from the lateral moraines induced by glacial tongue thinning;
e) the collapse of ice-core moraine ridges.

Minor noises may result from falling boulders from rock walls facing the glacier. In this case, the recordable sound is produced by the impact of boulders on the ice, eventually followed by the noise produced by debris sliding or rolling on the glacier after the impact.

CONTINUOUS SOUNDS

Subglacial Stream

The sub-glacial stream emits a sound originating from the depths of the ice, characterized by a predominance of low frequencies, conveying a sense of threat and power. Its intensity varies slightly between day and night.

Glacial Moulin

The glacial moulin and surface stream are sounds that change in intensity in relation to thermal fluctuations. At night, the sound resembles a small trickling stream, while during the day, it takes on the characteristics of a very strong waterfall with higher frequencies.

Meltwater Cascade

The meltwater cascade at the glacier's front exhibits behavior similar to that of the glacial moulin, also responding to temperature variations and being audible even several kilometers away.

THE STUDY AREA AND THE DATASETS

The Adamello Glacier

The Adamello Glacier (46° 09′ 02″ N, 10° 31′ 50″ E) represents the widest glacier in the Italian Alps (Baroni and Carton, 1996; Salvatore *et al.*, 2015), which covered an area of 12.87 km^2 in September 2023 (Maggi *et al.*, 2023). According to the Italian Glaciers Inventory, (CGI-CNR, 1959, 1961 a,b, 1962) it is divided into multiple individuals while in the World Glacier Inventory (World Glacier Monitoring Service, 1989) it is divided into two main bodies. Specifically, the CGI Inventory covers the Upper Miller Glacier (No. 600), Corno Salarno (No. 603), Salarno (No. 604), Adamello or Pian di Neve (608), Adamè (No. 609), and Mandrone (No. 639). Instead, the W.G.I. (WGI, www.wgms.ch) merges all the glaciers on the Lombardy slope fed by the Adamello Pian di Neve (I-4L01024-06) but keeps the Mandrone Vedretta (I-4L01011-15) as an individual glacier. Lately in view of its glacial dynamics and morphological characteristics the Adamello Glacier was considered a glacial body (Salvatore *et al.*, 2015; Maggi *et al.*, 2023).

The Adamello Glacier (W.G.I I-4LOI024-06, I-4LOI011-15) in addition to representing the largest glacier in the entire Italian Alps is also the thickest glacier in Italy, with an estimated ice thickness exceeding 250 m at Pian di Neve (Carabelli, 1962; Frassoni *et al*, 2001; Picotti *et al.*, 2017; Maggi *et al.*, 2023; Di Stefano *et al.*, 2024); it is a highland glacier, classified as a "Scandinavian-type summit glacier" (Marson, 1906; S.G.L., 1992; S.G.L., 2012), and feeds multiple diffluences (Bonardi *et al.*, 1995; Baroni and Carton, 1996; Ranzi *et al.*, 2010). The origin of the glacial flow descending toward the Genova Valley (Mandrone Glacier) is generated at Adamè Pass while the vast plateau called Pian di Neve extends to the south and west of the Adamè Pass. The northern sector of Corno Bianco and glacial inflows from the cirques carved on the Lobbia ridge also contribute in feeding the tongue of the Mandrone Glacier. In the past, glacier hosted to the south of Mt. Venezia and other small glaciers housed in the cirques between Cresta Croce and Lobbia Alta also contributed to feed the Mandrone Glacier.

The Adamello Glacier was firstly described and mapped by Julius von Payer (1865, 1868) who provides a detailed geographic narrative of the upper Val di Genova, the Pian di Neve and the Adamello acrocorus. Among the earliest glaciological works on the Adamello Group, the contribution of Suda (1879) supplies not only direct observation of the Mandrone and Lobbia glaciers retreat, but also reports observations gathered from local oral tradition. The first systematic works for monitoring this glaciers date back to the early 20th century (Marson, 1906, 1912); they also contain some considerations and assessments of the state of the Mandrone front at the end of the last century.

In more than one century of direct observations, the Comitato Glaciologico Italiano (CGI) operators collected a great deal of data on frontal variation of the Mandrone Glacier, as well as several photographs and other observation on the entire Adamello Glacier (Astori and Togliatti, 1964; CGI 1928-1977; CGI 1978-2018; Baroni *et al.*,

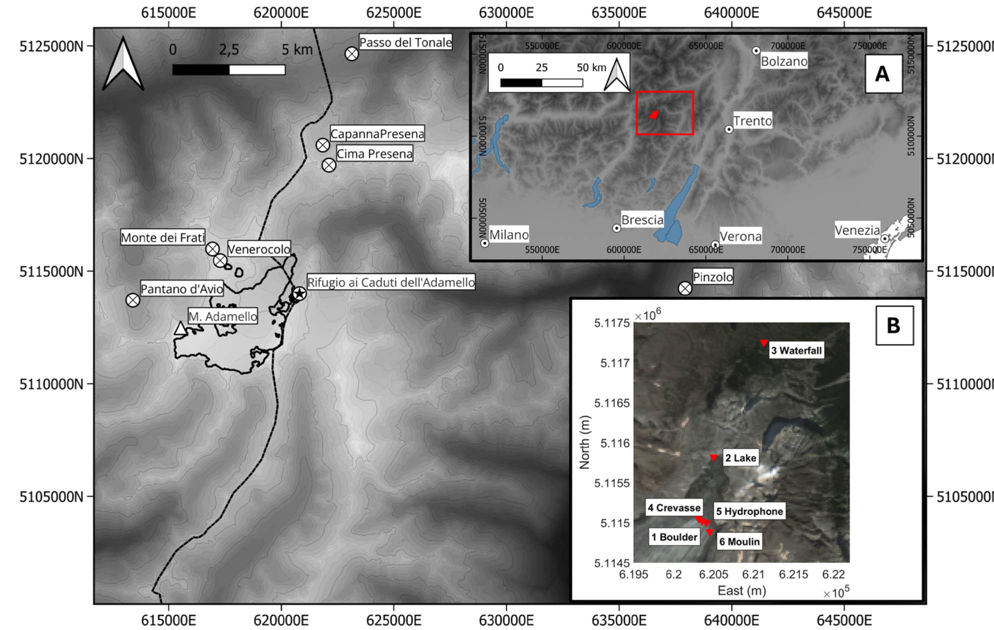

Figure 1 - Map of the location of the Adamello Glacier, showing major mountain huts (circled stars), peaks (triangles), and automatic weather stations (circled crosses). The glacier's boundary in 2022 are reported as a thin solid black line. The thick black line indicates the administrative boundary between the provinces of Trento (to the east) and Brescia (to the west). The map in the inset A locates the study area within the central Alps, in relation to major cities in northern Italy. The inset B shows the location of the recorders (red triangles) on a satellite image (Sentinel-2 RGB, 30 august 2024).

2011, 2023; Chiarle *et al.*, 2024). Actually, measurements of frontal variations are discontinuous and were interrupted during the I and II World Wars. Nevertheless, the time/distance curve reconstructed by Maggi *et al.* (2023) on the basis of frontal measurements supplied by CGI annual glaciological surveys, validated by means of historical maps and orthophotos, indicates a total retreat of the Mandrone Glacier front of 729 m from 1950 to 2022 CE. Considering the time interval 1919-2022 CE, the total withdraw of this glacier on the basis of annual glaciological surveys was 837 m (Merciai 1920, 1921a, 1921b, 1925; CGI 1928-1977; CGI 1978-2017; Baroni *et al.*, 2019, 2020a 2020b, 2022, 2023).

Referring to the maximum position of the glacier front reached during the Little Ice Age (LIA) maximum expansion (more than 25 km^2), reconstructed on the basis of geomorphological and glacial geological surveys (Baroni and Caron, 1996; Baroni *et al.*, 2014; Zanoner *et al.*, 2017), Maggi *et al.* (2023) indicate a total retreat of the Mandrone Glacier amounting to more than 2800 m.

The almost continuous frontal retreat ongoing since the end of the LIA was interrupted by short periods of stasis or by brief re-advances, registered during the '30s, the early '40s and the late '70s of the 20th century. Frontal retreat accelerated at an unprecedented rate during the last decades, with a pronounced acceleration in the last decade of more than 20 m a^{-1}. The front of the Mandrone Glacier gradually retreated from Pian Venezia (also named in historical maps "Malga Venezia" or "Venezia"), ascending by successive stages the channel incised in the steep escarpment downstream the Acquapendente threshold. In the 1920s the glacier established with a jagged front upstream of the same threshold.

The USIE acoustic data record (2021-2023)

Between the summers of 2021 and 2023 a series of field expeditions were conducted on the Adamello Glacier to acquire over 14,000 hours of acoustic data. The study took place over three summers with the devices operating between July 11th and September 23rd in 2021, between July 11th and September 20th in 2022 and July 18th and September 15th in 2023. This was achieved using five bioacoustic recorders (fig. 2) strategically placed across the glacier to capture the most subtle and hidden sound phenomena. These recorders were deployed to operate continuously, 24 hours a day, for several weeks at a time, providing a unique glacier's sound database. The bioacoustic recorders, supplied by Wildlife Acoustics, are specifically designed for long-term deployment in severe environmental conditions. They are equipped with high-capacity batteries that can last for weeks, ensuring continuous data collection. Additionally, the device also measures ambient temperature at regular intervals, providing additional information useful as a comparison for the mathematical model. Monthly on-site checks were conducted to assess the condition of batteries and memory cards, ensuring almost uninterrupted data collection. This approach facilitated detailed monitoring of acoustic and thermal variations, offering a comprehensive view of the dynamic processes involved. The recorders were used to monitor specific phenomena related to both morphology and acoustic events. The system of recorders was implemented in the Mandrone area, covering different zones with distinct environmental and altitudinal characteristics, including the periglacial zone near the glacier at 2400 m asl, the glacier front at 2600 m asl, and the first crevasse zone, characterized by crevasses and morphological variations.

Figure 2 - Photograph of the recorder of the USIE project.

One recorder was placed in the area of the glacier front near the meltwater waterfall, beneath a boulder, with the objective of capturing variations in water flow and monitoring related hydrological changes (from here this location will be called simply Waterfall and was a stable location throughout the 2021, 2022 and 2023 summer monitoring periods). Another recorder was installed inside crevasses in the Mandrone area (fig. 3), approximately six meters deep at the slope transition (from here Crevasse). The purpose here was to capture internal glacier sounds, including collapses, as well as the acoustic emissions of pressurized air bubbles being released by the subglacial stream – a phenomenon particularly evident during nighttime when surface melt slows. In one of the crevasses, where a subglacial stream was perceptible, recordings aimed to compare the low-frequency signals typical of subglacial processes with the high-frequency sounds associated with surface melting. A third recorder was placed also in 2021 inside a glacial pressurised well that channel and store surface meltwater and influences the flow rate in glacial conduits (Röthlisberger, 1972; Paterson, 1994). Suspended several meters using a steel cable anchored to a wooden bracket acting as a bridge, the recorder captured sounds from within internal water channels, providing valuable data on glacial hydraulic processes and capture sound transmitted through ice and water using specialized microphones in direct contact with these media (from here Hydrophone). A fourth recorder was fixed in summer 2021 to a stable boulder near the crevasse zone in the Mandrone area, intended to document atmospheric conditions such as rainfall and wind, and monitor human activity, (from here Boulder). Another device was located in summer 2022 upstream the crevasses area to document surface meltwater runoff into a glacial moulin (from here Moulin). A last microphone was installed in the year 2023, also sheltered under a boulder at the outlet of the subglacial stream into a periglacial lake, to document collapses of the glacier front and record the dynamics of instability events (from here Lake).

The acoustic monitoring system was equipped with a range of specialized sensors tailored to capture different types of signals within the glacial environment. High-frequency condenser microphones were employed to record

Figure 3 - Installation of the sound recorder in one crevasse of the Adamello Glacier during the 2022 campaign.

high-definition acoustic sounds in the air. Hydrophones, placed in direct contact with water and ice, enabled the detection of sound transmissions within both liquid and solid media. Additionally, contact microphones (geophones) were used to capture vibrations propagating through the ice, providing insights into sub-surface dynamics. All recorders were powered by lithium batteries, chosen for their long-lasting autonomy, which ensured continuous operation in outdoor conditions throughout the entire duration of each acquisition campaign.

The strategic placement of acoustic recorders across a variety of glacier zones enabled a comprehensive observation of glacial dynamics, capturing both surface processes and internal activity. By collecting data from multiple, environmentally distinct locations, it was possible to compare acoustic phenomena – such as collapses, flow variations, melting, and internal structural responses – offering an integrated and detailed perspective on glacial behavior. The use of diverse technological solutions, combined with environmentally sustainable materials like wood, allowed the system to adapt effectively to the variable conditions typical of the summer monitoring period. Altogether, this approach ensured the acquisition of reliable and representative data, essential for advancing the understanding of glacier dynamics through a multidimensional and innovative methodology.

In fig. 4 the consistency of the timeseries of the acoustic data records is represented for each device location.

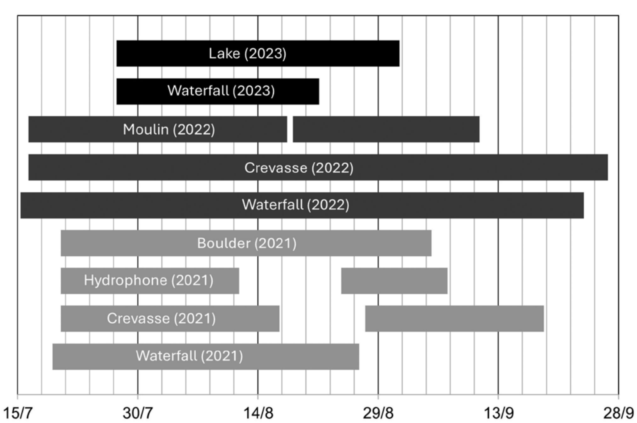

Figure 4 - Time windows of operation of the USIE recorders during the summers of 2023 (black), 2022 (dark gray), and 2021 (light gray).

Meteorological data and snow measurements

To accurately simulate the energy and mass balance of the glacier and effectively capture the diurnal variability in melt rates, the PDSLIM model requires meteorological variables recorded at an hourly temporal resolution. The input variables necessary to run the model include air temperature (°C), incident solar radiation (W/m²), atmospheric pressure (hPa), relative humidity (%), wind speed (m/s), and total precipitation (mm). These data are sourced from Meteotrentino, part of the Autonomous Province of Trento, and the *Servizio Glaciologico Lombardo* (SGL), a volunteer-based non-profit association focused on Alpine glacier monitoring. For each year, sub-hourly measurements (typically recorded every 10 or 15 minutes) are aggregated to an hourly timescale for the period from 1 April to 30 September. Given that the elevation of the glacier ranges from approximately 2600 to 3400 m asl, accurately representing the physical processes and meteorological variables at high altitudes is crucial. For this reason, we selected meteorological measurements from sites at similar elevations and as close as possible to the Adamello Glacier, building on the previous work of Ranzi *et al.* (2010). The stations selected to simulate the 2021, 2022 and 2023 energy and mass balance are reported in Table 2. We prioritized the stations with the lowest amount of missing data in the timeseries to ensure consistency.

METHODS

The PDSLIM model

The Physically based Distributed Snow Land and Ice Model (PDSLIM) is a distributed energy balance model developed to simulate snow and ice melt and the hydrological balance. It operates at an hourly temporal resolution using observed meteorological data and accounts for key energy fluxes, including net shortwave and longwave radiation, turbulent heat fluxes, advective heat from precipitation, and conductive heat fluxes in snow and ice layers. PDSLIM has been applied to estimate the mass balance over long periods and estimate the response to climate changes of the Adamello Glacier (Ranzi *et al.*, 2010; Grossi *et al.*, 2013; Colosio *et al.*, 2024) and to the Karakoram glacierised Naltar catchment (Liaqat and Ranzi, 2024).

The model is constituted by a semi-infinite layer of ice covered by two layers of snow (compacted and fresh snow), with the possibility to include a debris layer for a more accurate estimation of melt rates in regions where ice is covered by surface debris. Additionally, a module accounting for the deposition of dust and light absorbing material has been implemented and tested (Colosio and Ranzi, 2024). The model also integrates satellite-derived albedo from ASTER images for distributed ice albedo estimates. PDSLIM has been validated using in situ ablation stake measurements, snow cover observations, remote sensing snow cover data, and runoff in the downstream Sarca creek, demonstrating good agreement with observations. Simulations for the USIE projects were conducted for cells coincident with crevasses and moulins more suitable for verification of surface melt with high frequency sound signals and for the whole glacier's melt upstream crevasses and the outlet waterfall for verification with the low frequency acoustic signal.

Sound frequency, sound pressure and data processing

Sound travels as mechanical longitudinal waves, characterized by variations in pressure and displacement, through air or other mediums. An audio frequency (AF), or audible frequency, refers to a periodic vibration whose frequency, expressed in hertz (Hz), falls within the range that is detectable by the average human ear. The frequency of a sound primarily determines its pitch, with higher frequencies corresponding to higher pitches and lower frequencies to lower pitches. The range of frequencies audible to the human ear is limited, typically spanning from approximately 20 Hz to 20 kHz. However, the upper limit of this range often decreases with age. Sound pressure, or acoustic pressure, refers to the local deviation in pressure from the ambient atmospheric pressure caused by a sound wave. In air, sound pressure can be measured with a microphone, while in water, it is measured using a hydrophone. The SI unit of sound pressure is the pascal (Pa).

The data acquired by the recorders, after sampling, assumes a dimensionless value that represents the voltage value within a reference interval. This means that with a 16-bit analog-to-digital converter (ADC), the possible representable values will be in the interval [-32768, 32767]. These values, taken as is, have no physical meaning, and to have one they must be appropriately re-scaled. In fact, it is possible to trace back to the voltage value (V) at the time of sampling. This value will in turn be proportional to the sound pressure value (in the case of traditional microphones and hydrophones) or velocity (in the case of geophones and seismometers). Therefore, to arrive at the measurement of the physical quantity of the phenomenon that generated those values in the ADC, it is first necessary to know the dynamics, in Volts, at the input of the converters, any gain factors of the microphone preamplifiers and finally the sensitivity of the transducer element. In the case of a classic microphone, the sensitivity is usually expressed in (mV/Pa) and indicates how many millivolts the microphone capsule generates in the presence of a sound pressure signal measured in Pascals. Similarly, a seismic transducer will have a sensitivity that is measured in (mV/m/s), i.e. the voltage value (V) that is generated in response to a velocity, measured in meters per second, impressed on the sensitive element.

The recordings obtained from the USIE campaigns were processed in batch using Fast Fourier Transform (FFT) spectral analysis. The signal was decomposed into three sub-bands, referred to as the low frequencies (0-400 Hz), medium frequencies (401-1500 Hz), and high frequencies (1501-20,000 Hz) and then aggregated on an hourly scale. The exported audio data is in a linear scale, represents a sound pressure, L, is expressed in Pascals (Pa) and is calculated from ADC samples A by multiplying it with conversion factor C

$$L = AC \qquad (1)$$

$$C = \frac{V_{FS} \cdot M_{CAL}}{S \cdot N_{FS} \cdot G\sqrt{2}} \qquad (2)$$

Where V_{FS} is the full-scale voltage value of the recorder, M_{CAL} is a calibration factor of the microphone capsule (if present, otherwise it is assumed $M_{CAL} = 1$), S is the sensitivity value of the transducer in mV/Pa or mV/m/s, N_{FS} is the full-scale value of the numerical representation ($N_{FS} = 32768$ in the case of 16-bit signed sampling), G is the gain of the microphone amplifiers and the square root of 2 is a crest factor of the sinusoid, used to obtain the RMS value starting from a peak amplitude measurement.

To better align with human perception of sound pressure, the data is typically converted into decibels (dB). In acoustics, the sample value L represents the linear amplitude of the recorded sound pressure signal. However, from a perceptual perspective, the more relevant value is the Sound Pressure Level (SPL) expressed as

$$SPL = 20\ Log\ (L/L0\ ) \qquad (3)$$

Where L is the measured sound pressure and L0 is the reference sound pressure (L0 = 20 µPa for air). The SPL obtained is expressed in decibels, which is not a direct unit for a physical quantity. Instead, it is a logarithmic unit used to represent the ratio between two homogeneous physical quantities (or signal power in the case of circuits). In this way, a value of 0 dBSPL describes the softest sound that can be heard. Similarly, when the transducer element is, for example, a geophone, it is convenient to express the amplitude value referred to a value of 1 nm/s, and the unit is (dB re 1 nm/s).

In this analysis, atmospheric noises such as rain, wind, and rockfalls are not explicitly filtered out. Since rainfall and wind velocity are two inputs of the PDSLIM model and particularly relevant in the melting process, we expect to capture signal modifications due to such events in both the acoustic records and model simulations. Furthermore, the time duration of rockfall events is typically shorter than the time step of the model (1 hour), meaning that their acoustic energy is averaged out during the calculation of hourly sound pressure. The peaks associated with rockfalls are filtered by this averaging process.

RESULTS AND DISCUSSION

The data collected in the 2021 and 2022 campaigns

Glaciers are dynamic systems, and this vitality can be perceived through the rich spectrum of sounds produced at their surface and within their internal layers of ice and snow. Mechanical waves originate from various physical processes, such as ice movement, fracturing, and melting.

Table 1 - Classification of the sounds that can be heard on a glacier.

Code	Origin/type	Genesis	Agent	Occurrence	Subjective Duration [2]	Temporal Variability [3]	Loudness [2]	Soundscape Type [1]	Sharpness [2]	Tonality [2]	Source Recorder	Recording points Adamello Glacier
s1	Snow avalanche on the glacier surface	Primary	Snow	Occasional	minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	
s2	Collapse of snow bridge	Primary	Snow	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	
i1	Ice avalanche	Primary	Ice	Occasional	minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	1
i2	Ice fall from hanging fronts	Primary	Ice	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	1
i3	Calving of ice from ice cliff (dry)	Primary	Ice	Frequent	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	1, 2
i4	Ice calving in proglacial lakes	Primary	Ice	Frequent	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	2
i5	Opening of crevasses	Primary	Ice	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	4
i6	Seracs fall	Primary	Ice	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone, Condenser/Crevasse	1
i7a	Sinking of ice doline	Primary	Ice	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone, Condenser/Crevasse	
i7b	Collapse of ice cave	Primary	Ice	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone, Condenser/Crevasse	1, 2
i8	Roars produced by ice cracking and crevasse opening	Primary	Ice	Occasional	seconds	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone, Condenser/Crevasse, Hydrophone	5, 1
i9	Noise like snapping produced by ice cracking (thermal contraction)	Primary	Ice	Occasional	seconds	Variable	Not Loud	Geophony	Sharp	Not Whistling	Hydrophone, Geophone	5, 1
i10	Popping or crackling produced by air bubbles released by ice melting	Primary	Ice	Occasional	min/hours	Variable	Not Loud	Geophony	Sharp	Whistling	Geophone, Hydrophone, Condenser/Crevasse	1, 5
i11	Crackling induced by glacier flow	Primary	Ice	Frequent	sec/minutes	Variable	Not Loud	Geophony	Sharp	Not Whistling	Hydrophone, Condenser/Crevasse	5, 1
i12	Crackling induced by regular glacier flow	Primary	Ice	Persistent	hours/days	Variable	Not Loud	Geophony	Sharp	Not Whistling	Geophone, Hydrophone, Condenser/Crevasse	5, 1
i13	Icequake	Primary	Ice	Occasional	sec/minutes	Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Surface, Geophone, Condenser/Crevasse	
w1	Rain	Induced	Water	Occasional	min/hours	Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Surface, Hydrophone, Condenser/Crevasse	1, 5, 4, 6, 3
w1a	Thunder	Induced	Water	Occasional	seconds	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Condenser/Crevasse	1, 2, 4
w2	Oozing water in crevasses or in ice caves	Induced	Water	Recurrent	days/months	Not Variable	Loud	Geophony	Sharp	Not Whistling	Hydrophone, Condenser/Crevasse	6
w3a	Rustle of water flowing within a crevasse	Induced	Water	Recurrent	days/months	Not Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Crevasse, Hydrophone	6
w3b	water fall in bédière	Induced	Water	Recurrent	days/months	Not Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Crevasse, Hydrophone	6
w4	Supraglacial water flow in rills/gullies	Induced	Water	Recurrent	days/months	Not Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Crevasse, Hydrophone	6, 4, 5
w5	Supraglacial stream flow	Induced	Water	Recurrent	days/months	Not Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Crevasse, Hydrophone	5, 6
w6	Subglacial water flow	Induced	Water	Persistent	days/months	Not Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Crevasse, Hydrophone	4
w7	Melting water from glacier mouth feeding proglacial streams	Induced	Water	Persistent	days/months	Not Variable	Loud	Geophony	Not Sharp	Not Whistling	Geophone, Hydrophone, Condenser/Crevasse	2
d1	Rock/debris fall on glacier surface	Induced	Debris	Occasional	sec/minutes	Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Surface, Geophone	2, 1
d2	Rock/debris fall in a crevasse	Induced	Debris	Occasional	sec/minutes	Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Surface, Geophone, Condenser/Crevasse	4
d3	Rock/debris fall in proglacial lake	Induced	Debris	Occasional	sec/minutes	Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Surface, Geophone	2
d4	Collapse of ice-cored moraine	Induced	Debris	Occasional	sec/minutes	Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Surface, Geophone	2, 1
d5	Debris fall/slide due to differential ablation (e.g. on medial moraines or debris-covered gl.)	Induced	Debris	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	1, 2
d6	Fall from lateral moraine due to ice tongue thinning	Induced	Debris	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	1, 2
d7	Debris falling on lateral moraine	Induced	Debris	Occasional	sec/minutes	Variable	Loud	Geophony	Not Sharp	Not Whistling	Condenser/Surface, Geophone	1, 2
d8	Crackles in supraglacial debris	Induced	Debris	Occasional	sec/minutes	Variable	Loud	Geophony	Sharp	Not Whistling	Condenser/Surface, Geophone	
b1	Flying insect (e.g. beez)	External	Animals	Occasional	sec/minutes	Variable	Not Loud	Biophony	Sharp	Not Whistling	Condenser/Surface, Condenser/Crevasse	1, 4
b2	Flying birds	External	Animals	Occasional	sec/minutes	Variable	Not Loud	Biophony	Sharp	Not Whistling	Condenser/Surface	1, 2
b3	Bird chirping	External	Animals	Occasional	sec/minutes	Variable	Not Loud	Biophony	Sharp	Whistling	Condenser/Surface	1, 2
b4	Animal walking on the ice	External	Animals	Occasional	sec/minutes	Variable	Not Loud	Biophony	Sharp	Not Whistling	Condenser/Surface	
b5	Animal sounds	External	Animals	Occasional	sec/minutes	Variable	Not Loud	Biophony	Sharp	Not Whistling	Condenser/Surface	2, 3
b6	People walking on the ice	External	Human	Occasional	sec/minutes	Variable	Not Loud	Anthropophony	Sharp	Not Whistling	Condenser/Surface	3, 2, 4
b7	People talking/crying/singing	External	Human	Occasional	sec/minutes	Variable	Not Loud	Anthropophony	Sharp	Whistling	Condenser/Surface, Condenser/Crevasse	3, 4, 1
m1	Helicopter fly	External	Mechanic	Persistent	minutes	Variable	Loud	Anthropophony	Not Sharp	Not Whistling	Condenser/Surface, Condenser/Crevasse	2, 4, 1
m2	Airplane	External	Mechanic	Persistent	minutes	Variable	Loud	Anthropophony	Not Sharp	Whistling	Condenser/Surface, Condenser/Crevasse	
L1	Wind	External	Air	Occasional	sec/minutes	Variable	Loud	Anthropophony	Sharp	Whistling	Condenser/Surface	2, 3, 1
L1	Waterfall	External	Water	Persistent	days/months	Variable	Loud	Geophony	Sharp	Whistling	Condenser/Surface	3, 3

Table 2 - Meteorological stations characteristics and variables adopted to force the PDSLIM model for each simulated year.

Station name	Elevation (m asl)	UTM East (m)	UTM North (m)	2021	2022	2023	Operator
Capanna Presena	2730	621847	5120595	WS, RH, RAD, PRES	T, WS, RH, RAD, PRES	-	Meteotrentino
Cima Presena	3015	622121	5119708	-	-	T, WS, RAD, PRES	Meteotrentino
Monte dei Frati	3230	616949	5115988	T	-	-	SGL
Passo Tonale	1879	623132	5124651	-	-	RH	Meteotrentino
Pinzolo	760	637930	5114237	P	P	P	Meteotrentino

The acoustics phenomena described in table 1 are associated with a variety of events that are typical of the hydro-dynamics of the glacier itself. Thus, recording sounds of the glaciers is not only interesting from the artistic or bioacoustic point of view, but also can help us monitor and gauge the vital signs of the glacier itself.

Accurate classification of acoustic events allows researchers to quantify the frequency and nature of the underlying physical processes. Furthermore, the subglacial stream flow that is directly proportional to the upstream melting and rainfall, when present, can be estimated by monitoring the low or mid frequency sound pressure level at a given location of the glacier.

In fig. 5 we can see that the acoustic energy starts to rise at about 13:00 and reaches its peak at about 16:00. In this image we can clearly see the "breath of the glacier". By carefully looking at this image, we can already estimate which are the warmest days, which are colder, and how the temperature varies during the day. It's also interesting to take a look at the spectrogram of some of the sounds recorded on the glacier. The variety of sounds is wide, and it's obvious when we look at the spectrogram. In fig. 6 we report the timeseries of the sound spectrum of three different sounds. On the x-axis there is time and on the y-axis there is the frequency of the recorded signal.

Premiered at Ars Electronica 2022 in Linz, the work is a listening device that translates 24 hours of glacial melting activity on the Adamello Glacier into sound and sensory experience. It was installed also at the MUSIL Museum in Cedegolo (fig. 7) in the same year and in Brescia and other venues.

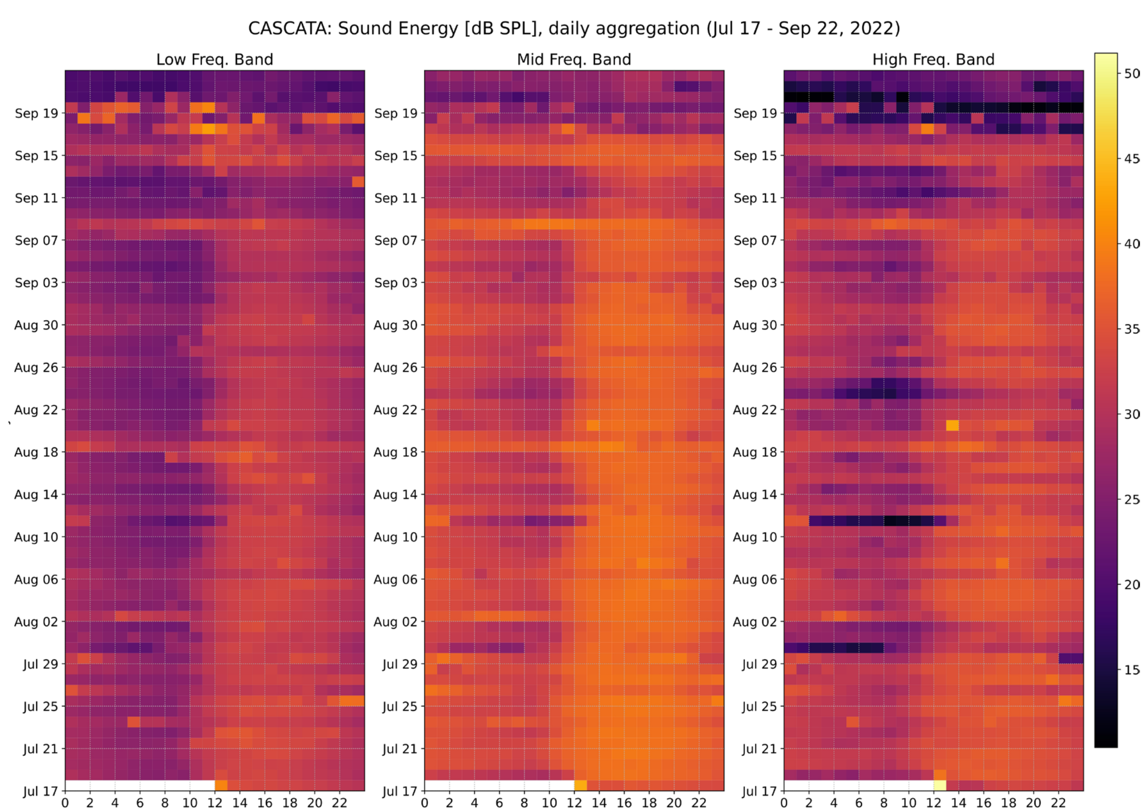

Figure 5 - Sound pressure level (Waterfall) at different frequencies. The time of the day is on the x-axis and the days are reported on the y-axis.

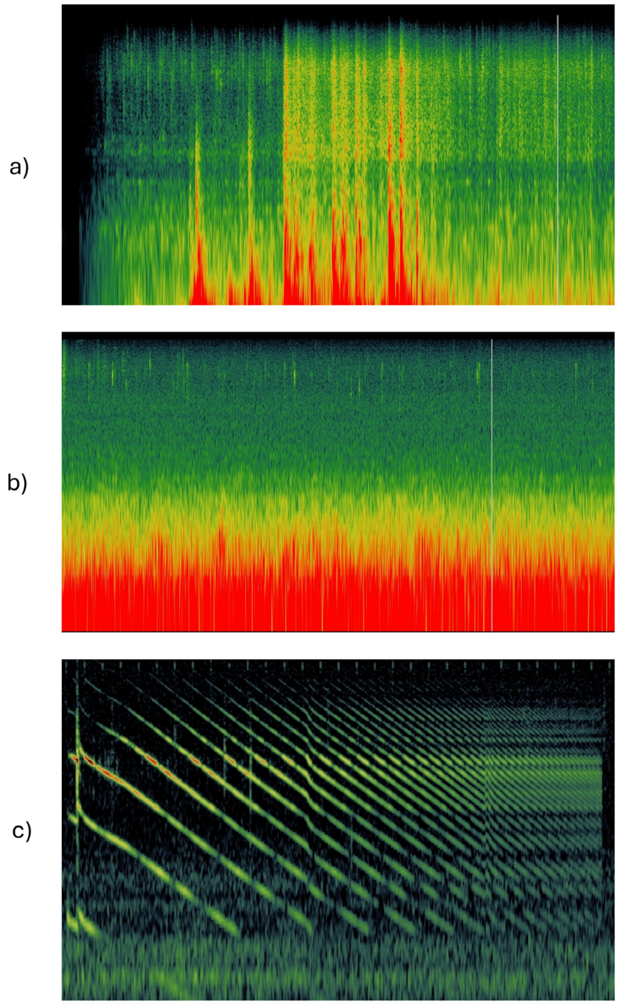

Figure 6 - Spectral time series of recorded sounds of some identified sources. a) Calving of ice from ice cliff (dry, i3 in table 1). b) Subglacial water flow (w6 in table 1). c) Popping or crackling produced by air bubbles released by ice melting (i10 in table 1).

Figure 7 - Artistic Sound Installation *Ablazione Sonora* installed at Ars Electronica in Linz and at the MUSIL Museum in Cedegolo, Brescia in September 2022.

The comparison with the simulated ice melt

We present here the comparison between the recorded sound pressure time series with the simulated melting rate for two cases: the recorders located at the Crevasse for the 2021 and the one located at the Waterfall in 2022 summer seasons. Sound pressure is logically connected with melt discharge because of the following reason: flow in streams, for instance in a waterfall or in a glacial channel, with a fixed drop height ΔH(m), dissipates its mechanical (potential and kinetic) energy at a rate P(W) proportional though the specific weight of water, γ, to its discharge Q(m^3/s) and drop height, $P = \gamma Q \Delta H$. The mechanical energy dissipation is transformed mainly into heat flux, sound energy, and evaporation. Assuming that the acoustic waves pressure, L, is proportional to the energy dissipation ~L^2, the latter being proportional to flow discharge, we obtain that the sound pressure, L, is an indirect measure of melt discharge, Q. To test this hypothesis, the PDSLIM melt output was first compared with the sound recordings at the crevasse location. The 2021 sound data from the Crevasse is unfortunately of low quality until August 6^{th}. In fact, since July 22nd, the microphone operated only during the day, from 10 a.m. to 12 p.m., because of battery and data storage limitations; only after August 6^{th} continuous recording began. Following a subsequent repositioning, which increased the low-frequency sound pressure levels, the recordings exhibit a more consistent trend from August 26^{th} until September 18^{th}. Nonetheless, the period covering the first 18 days of September shows a strong coherence with the simulated melt flow, as evident in fig. 8. In this figure the melt simulated in a local grid point is represented. An even better correlation with the high frequency sound pressure signal can be found introducing an average delay of one hour between the meltwater generation and the inflow into the crevasse, computed assuming an exponential probability distribution of the waiting time between melt and flow into the crevasse. The melt flow peak on September 11^{th} is associated with a precipitation event that, however, does not correspond to a significant increase in the high-frequency sound signal. In contrast, the precipitation event on September 15^{th} shows a clear and simultaneous peak in high-frequency sound pressure, precipitation, and melt flow. A similar pattern is observed for the rainfall on September 16^{th}, which also exhibits a perfect match with the high-frequency sound signal. This discrepancy underlines a possible limitation in adopting high-frequency acoustic signals alone to detect the hydrological responses, especially when precipitation temporarily dominates over melt inputs. More generally, it suggests that a multi-frequency approach or integrating complementary indicators might be necessary to better picture the hydrological complexity of such events.

Although these measurements are incomplete or of low quality because of technical limitations that occurred in the first weeks of observation, they still demonstrate a strong coherence with the simulated meltwater discharge,

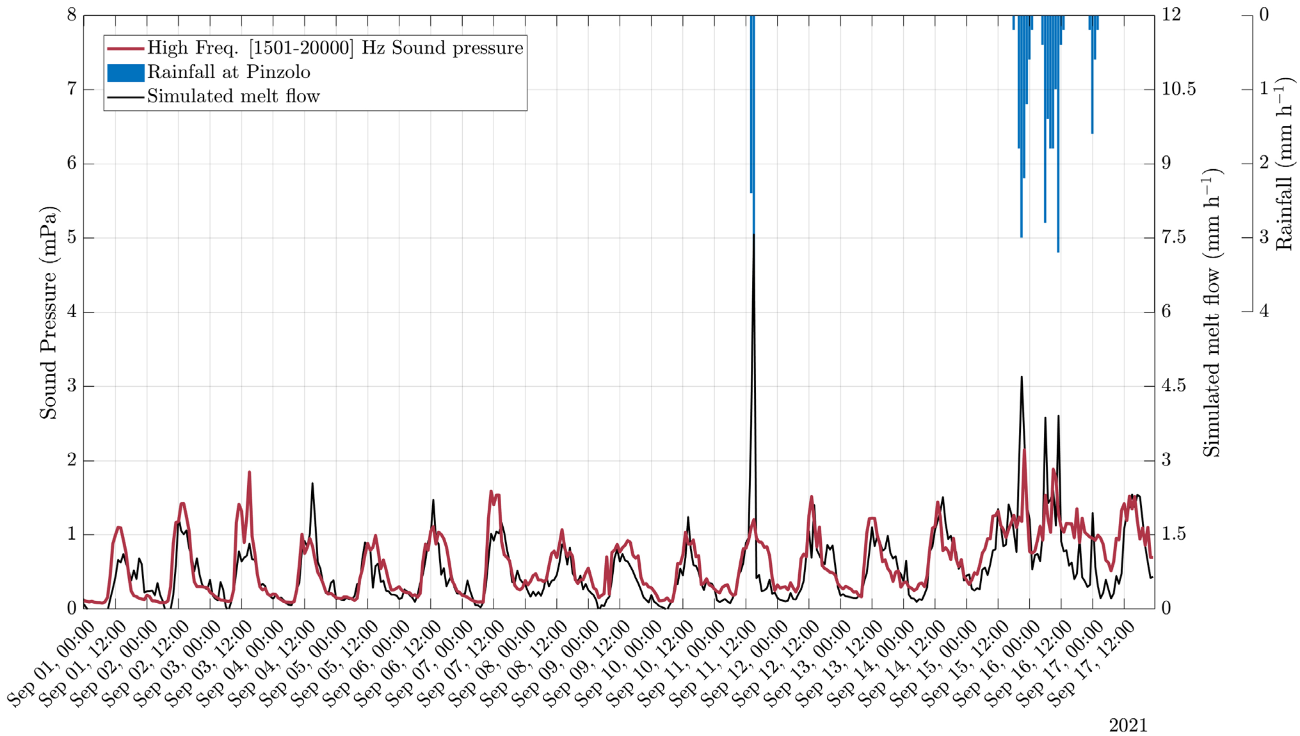

Figure 8 - Timeseries of high frequency sound pressure level recorded in September 2021 at the crevasse recording site (red) shown in fig. 1, simulated ice melt flow (black) and precipitation (blue). Rainfall-induced runoff events are marked by sound pressure and simulated melt and rainfall-induced flow peaks.

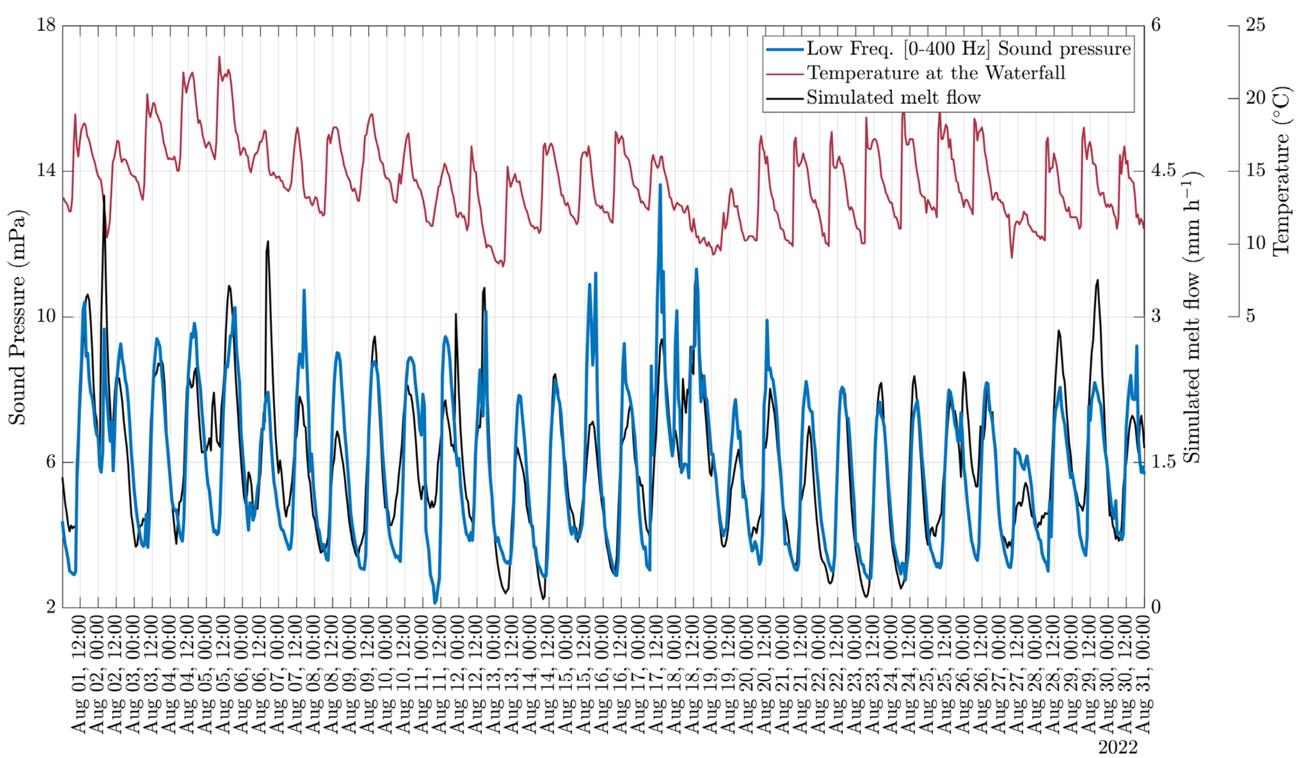

Figure 9 - Timeseries of low frequency sound pressure level (blue) and air temperature (red) recorded at the glacier's outlet waterfall recording site, and simulated ice melt rate (black) in August 2022.

confirming the potential of acoustic monitoring in glacial environments. However, to ensure their robustness and reliability for seasonal-scale model calibration and validation and long-term analysis, continuous data acquisition and the avoidance of mid-season repositioning are necessary, being consistency of the recorded timeseries a key factor for these applications of acoustic monitoring.

Differently from the crevasse case, the PDSLIM melt output for the comparison with the data recorded at the waterfall has been calculated for the entire glacier area as it fully contributes to the runoff. The sound pressure time series collected at the waterfall site during the 2022 campaign stands out for continuity and overall quality. Differently from the recordings at the crevasse in 2021, the signal does not show significant inconsistencies or anomalous values, allowing for a reliable interpretation of the acoustic variations for the entire month of August. In fig. 9 is clearly displayed a strong diurnal cycle in all three variables, i.e. low-frequency sound pressure (0-400 Hz), simulated meltwater flow, and air temperature at the site. Sound pressure and simulated flow follow similar daily oscillations, with peaks typically occurring in the afternoon hours, after the temperature maxima. An average time delay of four hours between melt generation and runoff at the waterfall, assuming an exponential distribution of waiting time between these two processes, maximizes the correlation coefficient between simulated flow and sound pressure signal at low frequency in August 2022. This delay, which varies with the melt rate intensity, is consistent with the expected hydrological response of the glacier, where solar radiation and air temperature drive meltwater production, as found in the literature (Lang, 1973). The coherence between sound pressure and simulated melt flow are generally high, with R^2 values reaching 0.64 and linear Pearson correlation coefficient equal to 0.80 between simulated runoff and the sound signal this month.

The observed delay between meltwater production and the recorded sound pressure signal, one hour in the Crevasse in 2021 and four hours at the Waterfall in 2022, highlights the dynamic nature of subsurface routing. This suggests a non-linear, non-static relationship that should be accounted for when using acoustic data for hydrological model calibration and verification. On the one hand, this delay might represent a complication for model calibration; on the other hand, it can highlight subsurface hydrological routing response of the glacier.

CONCLUSIONS

In this paper we show how sound pressure signals recorded over summer field campaigns conducted in 2021, 2022 and 2023 for the USIE-*Un Suono In Estinzione* sound art project at some locations in, on and close to the Adamello Glacier can be useful to calibrate and verify a glacier's melt and runoff model. A taxonomy of glacier's acoustics is proposed and some of the sounds recorded in a crevasse, a moulin, and at the glacier's outlet waterfall are made available to show, on one hand, the scientific information about the sound energy dissipation proportional to melt flow, and on the other hand, the suggestive beauty of the sounds generated by the glacier's dynamics. The timing and amplitude of the simulated melt are in agreement with the recorded sound pressure after the calibration of the time delay between the simulated melt and the runoff at one crevasse in September 2021 and at the outlet waterfall in August 2022, resulting in one and four hours, respectively. Spurious noises resulting from atmospheric events as rainfall, winds, rockfalls can be identified. High frequency (1501-20,000 Hz) signals are better correlated to surface melt processes recorded at one crevasse inlet, while low frequency signals (0-400 Hz) are well in agreement with the overall glacier's melt recorded at the outlet glacier's waterfall. The emotional character of the sounds recorded in this STEAM project and their scientific value can be an effective way to raise the awareness of the public on the threats posed by the global warming to the future existence of many continental glaciers, as those in the Alps, but also of parts of the Greenland and Antarctica Ice Sheets and the cryosphere and hydrosphere as a whole.

SUPPLEMENTARY MATERIAL

Examples of "sounds of glaciers" registered by USIE Project can be heard online by playing the videos of the corresponding specific sound uploaded in the open access repository in Supplementary Material at https://doi.org/10.4454/8jshg673

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