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Recovering environmental information from steep Alpine ice – development of a lightweight decametric ice corer and first use at Grandes Jorasses (4208 m a.s.l., Mont-Blanc massif)

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Abstract. Ice aprons are very small (generally $< 0.1\,km^2$) and thin (generally < 10 m) perennial ice bodies located on steep slopes with a quasi-stationary shear regime, frozen to steep permafrost rock slopes. They occupy – mainly above the glacier equilibrium line altitude – a very small fraction of the ice-covered surface but, with their quasi-stationary shear regime, contain ice that is multi-centennial to multi-millennial in age, making them a potentially important glacial heritage. In order to study these ice masses in their full thickness, a lightweight 10 m long ice corer was specially developed and successfully deployed on the northern face of Grandes Jorasses (4208 m a.s.l.) in July 2023. This article describes the technical characteristics of the ice corer and how it was used on a large ice apron of one of the largest rock faces in the Alps. It also presents the strategies we intend to use to analyse the extracted 8.8 and 6.0 m long ice cores.

1 Introduction

Human activities have strongly modified the chemical composition of the atmosphere, even in very remote regions of the world. Since ambient air components (aerosols and gases) are encapsulated in the bubbles, the study of chemical compounds stored in solid precipitations and accumulated in ice provides a unique tool for obtaining information on the composition of the preindustrial atmosphere; on its natural variability; on various past natural phenomena such as climatic variations (like changing vegetation), volcanic eruptions, and large forest fires; and on the impact of human activities (Legrand and Mayewski, 2017). Information recorded in polar and mountain ice cores is invaluable to understand the preindustrial period and in anticipating the future evolution of the atmosphere (Delmas, 1992) in the context of climate change. Old ices are, thus, a planet's memory. Since the early 1960s, the scientific community focusing on ice cores and ice analysis has produced a large volume of scientific results from deep coring sites in Greenland and Antarctica. By analysing the ice cores extracted there, it is possible to reconstruct numerous environmental parameters over periods of several hundred thousand years in the case of polar ice sheets – like at Dome C (East Antarctica), where the European Project for Ice Coring in Antarctica (EPICA) has provided access to climate and environmental records covering the last 800 ka (Jouzel and Masson-Delmotte, 2010a; EPICA community members, 2004), i.e. more than eight glacial–interglacial cycles, and soon will cover 1.2 million years with the Beyond EPICA project (Chung et al., 2025) – and periods of several thousand years in the case of mountain glaciers in the Andes (e.g. Vimeux et al., 2009), Himalayas (e.g. Xu et al., 2010) or Alps (e.g. Lamothe et al., 2024). The climatic information provided is extremely rich. While the measurements made on the first ice cores mainly focused on the isotopic composition of the ice as an indicator of climate change (Robin, 1977; Petit et al., 1999), the number of parameters studied has steadily increased, encompassing numerous measurements made on trapped air bubbles, on various impurities, and on the ice itself (Jouzel and Masson-Delmotte, 2010b). Brook and Buizert (2018), for example, highlighted the close links between greenhouse gases, aerosols, and the global climate over the last 800 000 years. Kaufman and Broadman (2023) rely, in particular, on ice cores from Antarctica to assess whether anthropogenic global warming was preceded by a long-term warming trend or by global cooling. Furthermore, Eichler et al. (2023) propose a reconstruction of anthropogenic air pollution in western Europe as preserved in various Alpine ice cores, such as major inorganic aerosol constituents, black carbon, and trace species.

Apart from polar ice sheets, ice caps, and the highest parts of the accumulation zones of mountain glaciers, another ice source of information has been investigated over the last few decades: ice caves, cavities that are usually karstic and which contain perennial ice that is sometimes from over a thousand to several thousand years old (Holmlund et al., 2005; Ravanel et al., 2024). Most are located beyond the altitudinal and latitudinal limits of glaciers. They are very interesting for reconstructing some local parameters such as stable isotope behaviour (Perşoiu et al., 2011), pollen (Feurdean et al., 2011), fungi (Brad et al., 2018), and North Atlantic Oscillation (NAO) control (Stoffel et al., 2009).

A last potential source, mentioned by Guillet et al. (2021) and further developed by Ravanel et al. (2023), corresponds to ice aprons (IAs) in steep high-Alpine slopes. Apart from a study by Xu et al. (2021) on a mid-latitude ice apron (wrongly called a "hanging glacier" by the authors as it does not have a steep front) in the Tien Shan (western China) based on repeated terrestrial laser scanning surveys during the period 2016–2018, IAs have so far only been studied in the Mont-Blanc massif (western European Alps). They are very small (generally $< 0.1\,km^2$) and thin (generally $< 10\,m$) ice bodies with more or less irregular outlines due to high ruggedness topographies and frozen to steep ($> 40°$) permafrost slopes with a quasi-stationary shear regime (very low ice creep and no basal sliding), mainly located above the regional glacier equilibrium line altitude, in a permafrost context (Ravanel et al., 2023). The almost near-zero movement of the ice is explained by the small ice thickness coupled with the cold context. The limited thickness keeps stresses and strain rates small; when thickness increases, shear stress increases, and the ice body starts flowing, forming a hanging glacier. Due to their very small size, IAs occupy a very small part of the ice-covered surfaces, and, recently, they have been shown to be able to lose several tens of centimetres of thickness during a single hot summer (Ravanel et al., 2023). The significant retreat of the IA on the northern face of Tour Ronde (3792 m a.s.l., Mont-Blanc massif) over the last few decades has caused major rockfalls: the IA no longer provides its important protective function for rockwall permafrost, while the surface ice no longer supports the rocks in areas that are generally highly fractured (Ravanel et al., 2023). This shrinkage also leads to a darkening of the mountain appearance, increasing difficulties for mountaineering (Mourey et al., 2019). This also represents a threat of the disappearance (Guillet and Ravanel, 2020; Kaushik et al., 2022) of these ice masses that could be several thousand years old (Guillet et al., 2021). IAs could thus constitute true – but increasingly disappearing – paleo-environmental archives.

To evaluate this potential, ice sampling necessitates the design of a dedicated lightweight corer compatible with mountaineering techniques, the development of which we describe in detail herein. It was successfully used for the first time on one of the largest IAs in the Mont-Blanc massif, the Linceul, on the northern face of Les Grandes Jorasses (4208 m a.s.l.), almost 9 m thick in the drilled zone.

2 Ice aprons as potential paleo-environmental archives

2.1 Overview of ice cores from the Alps

To date, in mid-latitude mountains such as the European Alps and other high-altitude sites around the world, ice cores have been taken from cold glacier accumulation zones, firn, or rock glaciers. These ice cores are archives of past climates (e.g. temperature) and atmospheric compositions (e.g. CO_2 or NO_3^- concentrations) of the Holocene. The time periods covered by these archives range from a few decades to several centuries (Maggi et al., 2006), with varying resolutions (seasonal to multi-year). The longest European Alpine sequences have been obtained from (i) high-elevation and low-accumulation glaciers such as Colle Gnifetti (4455 m a.s.l.) on Monte Rosa (4634 m) at the Swiss–Italian border, with accumulation rates estimated to be 0.20–0.35 m water equivalent per year ($m\,w.e.\,yr^{-1}$) and where the estimated age of the deepest ice is about 10 000 years (Jenk et al., 2009; Gabrieli and Barbante, 2014), or (ii) high-accumulation Alpine sites such as Col du Dôme in the French Alps (4236 m a.s.l.; about $2.5\,m\,w.e.\,yr^{-1}$; Preunkert et al., 2000), with a recent 1000-year reconstruction of NO_3^- concentrations (Lamothe et al., 2024). High-accumulation sites show a finer resolution with cyclical seasonal accumulation (summer–winter) due to a minimal post-depositional snow erosion (Maggi et al., 2006).

Ice cores from Alpine glaciers allow the reconstruction of parameter evolutions of European climate history. Temperature is estimated using the stable water isotope proxies $\delta^{18}O$ and δD (Jouzel et al., 1997) as signal changes with altitude could be modified by processes such as melting and refreezing, diffusion, snow removal by wind, and sublimation (Mariani et al., 2014; Huber et al., 2024).

Alpine glacier ice also records past environmental changes, such as ecosystem dynamics (e.g. vegetation types; Brugger et al., 2021); climate variations (e.g. temperature oscillations; Schöner et al., 2002); natural events (e.g. volcanic ash; Luongo et al., 2017); and human activities, e.g. pollution from industrial activities (Arienzo et al., 2021), biomass burning (Müller-Tautges et al., 2016), and microplastics (Ambrosini et al., 2019) at different scales (local, regional and global). These developments could be tracked through concentrations of chemical compounds (inorganic and organic fractions) and biological identification as pollen.

2.2 Dating and age model at Triangle du Tacul

Guillet and Ravanel (2020) hypothesised the IAs' ice to be quite old but with no clear insight into the potential age. Knowledge about ice ages in deeper layers – in particular, close to bedrock – was thus needed. The refinement of radiocarbon measurement techniques for microscopic organic material from glacier ice (Uglietti et al., 2016; Hoffmann et al., 2017) and its successful deployment for cold Alpine glaciers (e.g. Jenk et al., 2009; Bohleber et al., 2018; Hoffmann et al., 2018; Preunkert et al., 2019a, 2019b; Bohleber, 2019; Legrand et al., 2022) made it relevant to estimate the age of IAs' ice.

Particulate organic carbon (POC) content and radiocarbon dating, suitable for potential ice ages older than a few hundred years, have thus been carried out by Guillet et al. (2021) on a 0.6 m long ice core with a diameter of 5.5 cm, drilled into bedrock in April 2019 at Triangle du Tacul (3970 m a.s.l., Mont-Blanc massif, French Alps) using a portable drilling system (Fig. 1) developed for drilling over a few dozen centimetres in technical terrain like waterfall ice (Montagnat et al., 2010). At the date of the coring, the sampled IA was lying between 3570 and 3690 m a.s.l., extending over 4000 m^2, with a mean slope of 59°. The retreat of the IA since the 1940s has been quantified by Guillet and Ravanel (2020): it has lost close to 20 % of its 1940s surface area, with a noticeable increase in the mean melt rate since the 1990s.

Triangle du Tacul was selected since the access from the Aiguille du Midi cable-car and the climb to this IA are neither very long nor particularly exposed to rock and/or ice falls (in 2019). Also, previous on-site drilling for temperature measurements made with a portable steam-driven ice drill (Heucke, 1999) showed that the ice apron was only < 1 m thick at the drill site, allowing the extraction of a complete surface-to-bedrock cross-section. Temperature was recorded continuously between 1 April 2017 and 31 March 2018 in a 1 m deep borehole. Owing to the limited IA thickness, the thermal regime of the ice is highly sensitive to atmospheric forcing. During summer 2017, an ablation of 48 cm in the vicinity of the borehole resulted in the exposure of three of the four thermistors, initially positioned at depths of 10, 30, and 50 cm. As a consequence, only the data from the rock–ice interface can be considered to be representative of annual conditions, yielding a mean annual temperature of −8.1 °C. At this depth, the annual thermal amplitude is exceptionally high due to the reduced ice cover, ranging from 0 °C on 6 August 2017 to a minimum of −20.2 °C on 20 February 2018 (Ravanel et al., 2023).

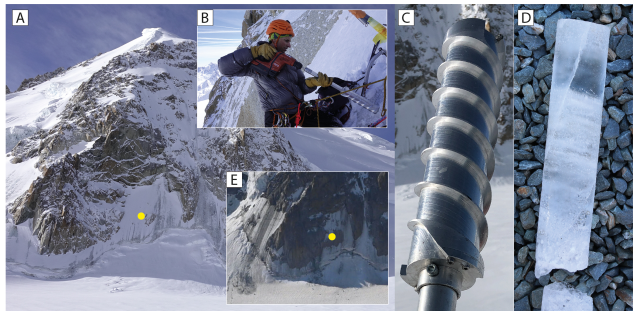

Figure 1. Short ice coring (0.6 m) at Triangle du Tacul (3970 m a.s.l., Mont-Blanc massif, France) using a corer previously developed for the purposes of a study on waterfall ice (Montagnat et al., 2010). **(A)** Triangle du Tacul on the day of drilling in April 2019. **(B)** Drilling with a light portable drilling system perpendicular to the surface of the ice apron (IA). Panels **(C)** and **(D)** show the corer and a part of the ice core. **(E)** The drilling site at the end of August 2024; the cored ice has disappeared.

In their study, Guillet et al. (2021) noted that the fraction derived and denoted as particulate organic carbon (POC) – prior to the time of anthropogenic fossil fuel combustion – originated mainly from direct primary emission of the living biosphere and is therefore well suited to ^{14}C dating (Jenk et al., 2006, 2009; Uglietti et al., 2016; Hoffmann et al., 2018). The two dated samples, taken from depths of 30–40 and 40-50 cm, respectively, have mean calibrated ^{14}C ages of 630 ± 55 and 2840 ± 175 years cal BP. Considering the small thickness of the IA, a strong increase of ∼ 2000 years over such a short interval of 10 cm might be a surprise. However, the order of magnitude of the age–depth gradient and the absolute ice age 10 cm above bedrock (∼ 3000 years cal BP) are comparable to those already detected for basal ice in high-altitude cold Alpine glaciers: ∼ 4000 years cal BP (Hoffmann et al., 2018) and > 10 000 years cal BP (Jenk et al., 2009) for two different ice cores drilled from Colle Gnifetti (4450 m a.s.l., Monte Rosa region, Switzerland), ∼ 7000 years cal BP at Mount Ortles (3905 m a.s.l., eastern Alps; Gabrielli et al., 2016) and Piz Murtèl (3433 m a.s.l., Grisons, Swiss Alps; Bohleber, 2019), ∼ 5600 ± 600 years cal BP at Col du Dôme (3436 m a.s.l.; Mont-Blanc massif, France; Preunkert et al., 2019b), while a ∼ 5000-year-old ice has been found at the Chli Titlis cold-based glacier (3030 m a.s.l., central Switzerland; Bohleber et al., 2018).

With the ice becoming older with increasing depth and due to glaciological flow characteristics, as predicted in models (e.g. Haeberli et al., 2004) and directly documented (Uglietti et al., 2016), the age gradient with depth becomes strongly enhanced near bedrock. Assuming an absence of basal melting in the past and considering a largely regular shear deformation parallel to bedrock, as suggested from ice texture investigations, Guillet et al. (2021) hypothesised the deepest part of the ice at the Triangle du Tacul to be (much) older than 3000 years. It is worth noting that the ice that was cored in 2019 disappeared completely during the summer heatwaves of 2022, 2023, and 2024, which were generally extremely damaging for Alpine glaciers (Cremona et al., 2023). Thus, the ice still in place today on this type of IA could be even older than the oldest ice from the 2019 Triangle du Tacul ice core.

2.3 A new source of paleo-environmental information – what to look for

The results obtained from the Triangle du Tacul ice core (2019) indicated not only the presence of ice thousands of years old (at least 3000 years) but also the presence of ammonium oxalate in the deepest part of the ice core, with an enhancement by a factor ~ 55 compared to the close Col du Dôme ice at the beginning of the 20th century (Preunkert and Legrand, 2013). As demonstrated for the basal layers of the Greenland GRIP ice core (Tison et al., 1998), the existence of considerable deglaciated areas with significant plant cover in the vicinity of the ice formation site leaves this chemical footprint during the formation of the ice apron (Guillet et al., 2021). IAs could therefore provide information about periods during which the cold ice masses were equivalent to the present ones or even smaller. It is therefore necessary to core different IAs down to the bedrock in order to date and study the basal ice. Similarly, high-resolution dating of ice cores from IAs could provide information about some long periods of melting (or lack of accumulation) at the surface of these ice masses. This could thus give a new outlook on the ice cover and climatic evolutions of the high-Alpine mountains over all or during part of the Holocene.

For periods when recording in ice is good and sufficiently continuous (no melting or gaps in the accumulation), it could be possible to study certain local atmospheric transports (types of vegetation, local sources of contaminants, local human activities) or even more regional and distant sources (fires, biomass burning events, Saharan dust storms) or even global sources (climatic changes with meteorological conditions favouring the formation or disappearance of ice). One of the limitations is that little is known about the mechanisms by which ice accumulates on IAs (including small annual ice thickness, non-continuous record, wet snow and refreezing meltwater, complex stratigraphy with discontinuities), with effects on the elements sought out as post-depositional inputs (surface with prolonged exposure to the atmosphere during a hiatus). In any case, the ongoing climate change is responsible for a compromised preservation of these archives (Guillet and Ravanel, 2020; Kaushik et al., 2022; Ravanel et al., 2023), and it is necessary to accelerate research as long as these cryospheric objects are still present.

3 Development of a lightweight coring tool for application on steep slopes

3.1 Available corers and limitations for steep slopes

The coring systems currently in use in glacier contexts consist of a mechanically welded frame including a winch and a tilting mast that can be moved from a horizontal position to extract the ice core and carry out mechanical and electronic maintenance on the various parts of the corer to a vertical position used for coring operations, with sometimes very high levels of complexity (e.g. Bentley et al., 2009; Gibson et al., 2014). The ascent and descent of the corer are controlled from a control panel, and the corer motor requires an electric cable to drive it. A generator is also required to power the various electrical and electronic components (control panel, load cell, coring motor, and winch).

The weight of such equipment varies between several dozen and several hundred kilograms, requiring the use of a helicopter or an aircraft for transport in mountain areas (e.g. Preunkert et al., 2000, 2019b; Zagorodnov et al., 2005) or caterpillar-tracked machines on ice caps (e.g. Motoyama, 2007; Zhang et al., 2014). This makes their use on steep Alpine faces very difficult, if not impossible, along with the impossibility of moving them using mountaineering techniques. In addition, the mechanical operation of these corers makes them usable only on horizontal surfaces (flat parts of glaciers, mountain passes).

The only coring systems that can potentially be used on steep slopes are the Mark II (Fig. 2a) Sipre and Kovacs from Kovacs (https://kovacsicedrillingequipment.com). These are made from standard aluminium or stainless steel, making them heavy and difficult to handle on steep slopes. Using 7075 aluminium and carbon fibre would make the corer much lighter and easier to handle, with excellent mechanical strength. Furthermore, we need a corer that can be used with a lightweight hammer drill. However, the Sipre is essentially manual, while the others require dedicated powered equipment. We also need cutting tools that are commercially widely available, easy to replace in the field, and cost-effective, which is not the case with Kovacs. A low-aggression profile would also reduce the risk of jamming, a common issue with traditional sharp-edged tools used in Kovacs systems. From a surface treatment perspective, the anodised aluminium components would reduce friction and ice or snow adhesion on the coring tube, which improves sample quality and drilling ease. This is not found in standard Kovacs models.

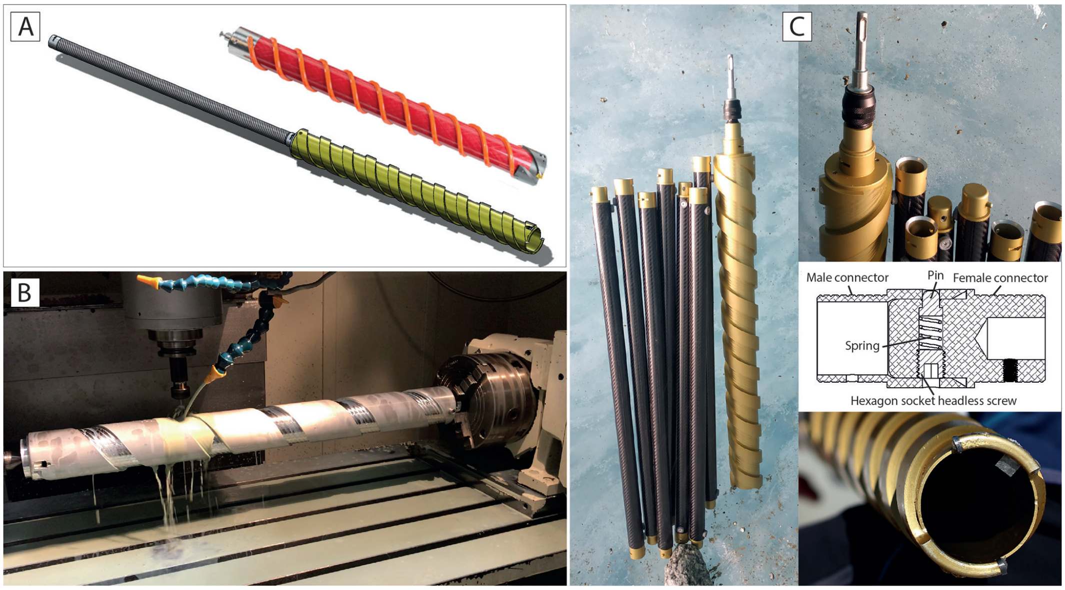

Figure 2. Development and construction of a lightweight decametric ice corer. **(A)** A 750 mm long core tube with a drilling head (view: Solidworks) under the Kovacs Mark II coring system (9 cm diameter ice core up to 1 m long). **(B)** Machining of the aluminium tube. **(C)** The anodised corer with an SDS drill bit mounting system for using a drill and its carbon extensions with male and female quick connectors. Note the tungsten carbide pellets on the drill head and the core locking mechanism.

3.2 Development of a lightweight decametric ice corer

In order to meet the specific needs of scientific work on very steep slopes (> 40° and up to vertical), several components have been redesigned, and others have been replaced or removed from the systems usually used on flat glaciers.

The frame (mast, winch) has been removed. Core depth and speed have to be controlled manually. The new corer can be operated either manually or with a portable electric drill. This is the most important change in the working principle of the corer, resulting in a considerable weight saving (it can be moved using mountaineering techniques) and a significant simplification of the system.

The coring system, which usually consists of an anti-torque part, a motor, an ice chip chamber, an outer tube, a core tube, and a drill head, has been thoroughly simplified. Only a core tube with a drill head has been retained (Fig. 2a). The standard dimensions of a core tube are a minimum of 2 m, and the diameter of the drill head is 140 mm outside and 99 mm inside.

New design work was carried out, and the dimensions of the corer were adapted for steep-wall applications. The core tube was reduced to a length of 750 mm, with an outer diameter that is as small as possible to give an inner diameter of 60 mm (diameter of the ice core). The cutting-tool portion of the drill head, which is usually custom designed and manufactured, was replaced with tungsten carbide pellets. The outer tube used to transport the ice chips has been eliminated as it was initially attached to the motor part for a standard corer, although an ice chip chamber would have been considered after the test phase (see Sect. 3.4). These changes greatly simplify maintenance operations and mean that the operator's experience with coring can be much shorter than with standard ice corers. The choice of materials was crucial in order to meet the weight requirements of the system and its portability in steep walls.

3.3 Construction, structure, and materials

The study and design of the coring system (Fig. 2A) were carried out using Dassault Systems' Solidworks, a 3D design tool. In accordance with the requirement specifications, an initial design phase was carried out to establish the basis of the general system and its feasibility. An initial 3D model was submitted by the French Ice Core Drilling Platform (F2G) of the Institute of Environmental Geosciences (IGE, France) to the Environment, Dynamics and Mountain Territories lab (EDYTEM), the end user of the product, where the design was validated and the requirement specifications were refined. The choice of carbon for the extensions and of aluminium for the core tube was based on their mechanical strength, which contributes to the structural strength of the corer, and their low weight.

The second phase involved the drive of the corer. This required major changes compared to the operation of standard ice corers and involved a number of different stages.

The design of the quick connectors (Fig. 2C) between the extensions of the coring tube required several iterations and mechanical simulations. The system uses quick connectors with a return spring that is released with a special key. Carbon tubes from the body of the extensions, in which the male and female parts of the quick connectors are embedded, form 75 cm long extensions for a total length of 9.75 m (13 pieces). Each quick connector is bonded with an insert at the end of the male or female part and secured with a screw that passes radially through the carbon body. A prototype was produced to test handling and reliability under field conditions. Carbon extensions were subcontracted to meet the delivery schedule for the corer.

A third phase dedicated to the coring tube was based on a previous study carried out by the IGE technical department on the requirements of a short ice corer for a study on waterfall ice around 2006 (Montagnat et al., 2010). This expertise guarantees the mastery of design and production.

A mechanical study was performed using Solidworks to determine the outer diameter of the core tube, which depends on the cutting tools. The other parameters were given in the specifications. The helix angle was adjusted to compensate for the removal of the outer tube. The purpose of this outer tube, which is found in standard coring systems (Bentley et al., 2009), is to assist in the transport of snow and/or ice chips, and it is attached to the motor of the corer. In the case of sub-horizontal drilling (perpendicular to the steep slope), the motor becomes external to the system. The annular space between the walls of the borehole and the outer diameter of the core tube had to be as small as possible to overcome ice chips conveying difficulties.

The core tube was manufactured on a digitally controlled machine in the IGE's engineering department. An aluminium tube was machined in a 12 h continuous machining operation using an extensive computer-aided manufacturing step (Fig. 2B). The part was then anodised to protect it from impact and wear.

Figure 3. Coring tests carried out in October 2021 **(A)**, June 2023 **(B)**, and July 2023 **(C)**. The first demonstrated the effectiveness of the drilling head but also the difficulties associated with the plugs formed by the ice chips. The second demonstrated the value of anti-vibration spheres fixed on the carbon extensions. The third showed the inefficiency of the chip chamber (black cylinder at the rear of the corer) and, one more time, the need to drill short sections of core to avoid ice plugs.

3.4 Ice corer test on Mer de Glace

Once produced, the corer was tested three times on the Mer de Glace glacier (Mont-Blanc massif), close to the ice cave (ca. 1600 m a.s.l.) at the Montenvers tourist site, which is easily accessible by rack-and-pinion train and cable-car. It should be noted that these tests were performed in tempered ice at the phase equilibrium temperature, containing water.

The first one was carried out in an ancient ice cave in October 2021 (Fig. 3A). The aim was to test (1) the efficiency of the drilling head and the drilling rate, (2) the evacuation of the ice chips, (3) the efficiency of the mechanism for locking the core in the corer before extraction (Fig. 2C), and (4) the mounting–dismounting of the carbon extensions. Drilling proved to be extremely efficient, with the drilling head having no difficulty penetrating the ice, driven by a 36 V drill. The evacuation of the ice chips was trickier because, although the first few centimetres of drilling saw the ice chips be well driven in the helix, they quickly created a mixture of ice chips (and liquid water) that stuck to the groove and above the corer, preventing subsequent chips from moving up the groove. This creates a plug with a high liquid-water content, which can even stop the corer being pulled up. A 4 m long ice core sample was taken, made up of around 15 elements. Only the first element is in one piece ($\sim$ 70 cm). The core elements are then, on average, about 30 cm long each as there is a proven risk for the corer to become blocked due to a plug of chips forming above the corer. The test also provided an opportunity to work on the tension of the core locking mechanism. Following this initial test, it was decided to build a chip chamber, a plastic cylinder which would surround the coring tube and its groove, thus preventing the ice chips from getting into contact with the ice on the borehole walls. With this, the core locking mechanism is effective if the ice core to be removed is first broken off at the bottom of the borehole; otherwise, the mechanism does not apply enough force on the ice core to break it off, and the core slides out of the coring tube. Before each ice core removal, a few energetic jerks are applied to the drill and, therefore, to the corer to help break up the core before extracting it. Several attempts are sometimes necessary. Finally, the mounting–dismounting of carbon extensions is fairly efficient as long as the tools required for the operation are attached so that they do not get lost on the slope.

The second test was carried out in June 2023 to assess anti-vibration spheres made of very light PLA plastic using a 3D printer and attached to the extension cables to centre them in the borehole (Fig. 3B). These proved to be very effective. The test also provided an opportunity to define a methodology for making the various handlings as efficient as possible under real conditions.

The chip chamber was finally tested on 3 July 2023 (Fig. 3C), the day before the main mission. The presence of liquid water was a problem for the chamber. The large quantity of liquid water was linked not only to the operation of the corer, which produces it as a result of friction in ice whose temperature is at the melting point (temperate ice) but also to the meltwater (runoff) present on the surface of the ice due to the high air temperature and solar radiation on the day of the test. In view of the numerous experiments carried out by the authors with the "waterfall ice corer" (Montagnat et al., 2010), during which this problem of ice chips and/or liquid water did not arise, it seems that the evacuation problem identified here stems, in particular, from the temperate thermal regime of the ice and the melting on that day. This problem might not arise in cold ice, characteristic of IAs (Ravanel et al., 2023), where the action of the corer seems not to be sufficient to produce enough liquid water to form a plug and to prevent the evacuation of the ice chips. However, it was decided that, even in cold ice conditions, the chip chamber would not necessarily be used, and no attempt would be made to extract ice core elements the length of the corer, and only elements of around half the length (ca. 35 cm) would be collected. In this way, the chips would be evacuated each time the corer is removed from the IA.

4 The north face of Grandes Jorasses (4208 m a.s.l.) as the coring site

4.1 Place of "Linceul" in the ice aprons of the Mont-Blanc massif

At the end of the summer of 2023, there were nine IAs remaining on the Grande Jorasses northern face (4208 m a.s.l.; Fig. 4A–C). Based on an analysis of orthophotos taken on 24 August 2023 by the National Geographic Institute (IGN), these IAs have a surface area of between 932 and 31 288 m^2. The largest one is the "Linceul" (the "Shroud"), an IA located 390 m above the Mont Mallet glacier, a tributary of the Mer de Glace, the largest glacier in the French Alps. Perched on the upper half of the face, the Linceul can be seen from the arrival area of the Montenvers train station (Fig. 4A). The Linceul is the largest and highest in altitude. Its maximum width is 115 m, and its maximum length is around 440 m. Its minimal altitude in September 2023 was around 3510 m a.s.l., and its maximal altitude was 3952 m, i.e. well above the regional glacier equilibrium line altitude ($\sim$ 3000–3100 m according to Rabatel et al., 2013) in a permafrost context (Magnin et al., 2015). The presence of permafrost

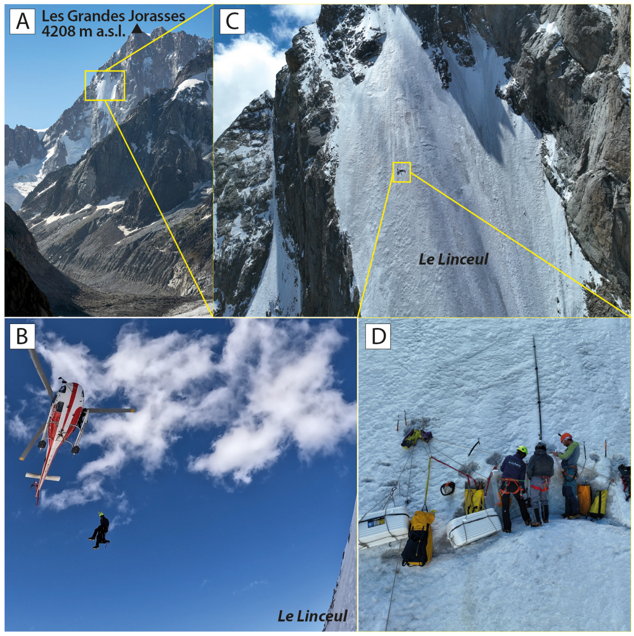

Figure 4. The coring mission on 4 July 2023 in the Linceul, the main IA of the Grandes Jorasses northern face (**A** and **C**; 4208 m a.s.l.). **(B)** Winching operation. **(D)** Organisation of the drilling site with two large iceboxes.

is also suggested by the mean annual temperatures of ~ -5 and -8 °C measured at the base of two IAs of the Mont-Blanc massif (Ravanel et al., 2023). The slope angle of the surface is quite constant throughout this IA, between 50 and 55°. Following the work of Kaushik et al. (2022) on IAs of Mont-Blanc massif, the Linceul was noted to be the 22nd in size when considering all types of IAs of the massif. But, taking a look on this classification, this IA, with a surface area of 36 044 m^2 in 2019 (determined using GIS data from Kaushik et al., 2022), is the largest type-1 IA in the Mont-Blanc massif. A type-1 IA is defined as a "long-standing exposed IA", i.e. an IA which continuously existed independently of any glacier under Holocene climatic conditions according to the classification of Ravanel et al. (2023). The altitudes of the Linceul make it the highest type-1 IA in the Mont-Blanc massif (data from Kaushik et al., 2022). There is another type-1 IA on the Grandes Jorasses northern face, at the beginning of the Colton MacIntyre route. Other IAs of the face are type-4 IAs, defined as "IAs that overlook hanging, slope, or cirque glaciers".

4.2 Logistics for the July 2023 mission

The team consisted of three people, all highly experienced in mountaineering and rope access. The equipment needed included the corer with new tungsten carbide pellets; 12 75 cm long carbon extensions; the 36 V drill used during the test phases and a back-up drill; small technical equipment for mounting and dismounting the extensions and for carrying out repairs if needed; a chainsaw to create a ledge in the ice for work; the mountaineering equipment for the whole team, including approx. 50 m of static ropes to secure the coring zone and two 60 m long dynamic ropes in case it became necessary to evacuate from above (ice climbing) or below (rope abseiling); and two large iceboxes to store some of the equipment first and then the ice cores.

Given the volume of the equipment required, access was only possible by helicopter. The team and then the equipment, in a big bag, were first brought up from Chamonix to the Couvercle refuge (2679 m a.s.l., 5 km NNW of the coring site). In order to test the aerological conditions for flying and winching, the first member of the team was winched about 20 m to gain a foothold in the centre-right of the Linceul IA, in a concave zone, which was itself thought to reflect a concave bedrock topography favourable to maximum thicknesses. Due to rockfalls in this sector, as soon as he was winched, he was moved some 40 m to the left (east) before setting a series of anchors (ice screws) into the ice to secure the other members of the team. Although the sector is more convex, it corresponds to the very central part of the IA, with thicknesses that are certainly among the greatest. The other two members of the team were then winched (Fig. 4B) to the coring site before the equipment was flown in.

4.3 Core sampling and extraction of the first "long" ice cores from an ice apron

The first action was to secure people and equipment by installing a series of anchors (ice screws and V threads) and a lifeline (static rope) over a horizontal length of ~ 6 m. Then, all along and downstream of the lifeline, a 1.2 m deep notch was cut in the ice using a chainsaw and ice axes. Once the working area was ready, with the iceboxes fixed beyond the notch so as to not interfere with the work, the first drilling began at approximately the centre of the notch, perpendicular to the slope (Fig. 4C). The chip chamber proved to be ineffective, and, given the obviously low temperatures of the ice (cold and dry ice), it was quickly abandoned. Particular care was taken not to attempt to extract elements that were too long to avoid the risk of blocking the corer due to a plug made of chips. The very regular extraction of short pieces of core (a few dozen centimetres) ensures that there is no blockage and that the ice extracted is of good quality. Each extraction is inserted into a plastic bag, numbered, and marked with the direction of coring. The cores are placed in a bed of crushed ice in the iceboxes. Extractions are increasingly tedious because of the depths involved, but it has not been necessary to dismantle all of the extensions each time, which saves a considerable amount of time. During the first core sampling (core 1), the bedrock was reached at 8.8 m (it was impossible to continue drilling, and the pads on the drill head became blunt). Because the first borehole was fast enough, a second borehole was drilled a few metres next to the first. This one (core 2) was stopped at a depth of 6.0 m due to the likely presence of a harder element and, above all, the late hour.

The equipment and cores in iceboxes were first transported by helicopter to the Couvercle hut and then the members of the mission before returning to Chamonix and storing the cores in a dedicated freezer at −24 °C at EDYTEM lab. Weather and air conditions remained good throughout the day. A drone flight was carried out to film the mission.

Core 1 (8.8 m) weighs 22.5 kg, while core 2 (6.0 m) weighs 15.5 kg. The texture of the ice is predominantly white (with numerous air bubbles) to transparent (virtually no air bubbles). Only a few fine yellowish levels of very fine silt break up this homogeneity.

It should be noted that no temperature measurement was carried out in the borehole. However, a specific borehole was drilled for this purpose in July 2024, but the temperature data are not yet available.

5 Conclusions and outlook

Considering the multi-millennial age of the ice in an IA cored in the Mont-Blanc massif in 2019, IAs could be good paleoenvironmental archives. To obtain the longest and most complete record possible, we wanted to drill a core in one of the largest and highest (in terms of altitude) IAs in the Mont-Blanc massif, the Linceul, on the northern face of Grandes Jorasses. To accomplish this very challenging task, we had to build a special, lightweight, and completely portable corer using mountaineering techniques. The corer, developed by a team specialised in glacier coring, consists of a 75 cm long aluminium corer and carbon extensions that allow drilling down to a depth of 10 m. After several test phases, the corer was used on the planned steep face and extracted an 8.8 m long ice core down to bedrock and another 6.0 m long one. Particulate organic ^{14}C dating will soon be performed to verify that the age of the ice exceeds a few thousand years at the base of the IA, to assess whether the record is continuous or not, and to create an age model before conducting studies of the chemical compounds and contaminants present in the ice. The thin yellow layers already hint at future results regarding Sahara dust storms. Before any new drilling can take place, the corer, which is already very efficient, will have to be improved so that it can remove ice chips more effectively.

Data availability. Detailed technical data on the lightweight decametric ice corer can be provided upon request to the second author (Romain Duphil – romain.duphil@univ-grenoble-alpes.fr).

Author contributions. LR conceptualised and supervised the research. LR, RD, EM, and OA developed the corer, and RD and OA produced it. LR, EM, and MF carried out the work in the field. LR prepared the paper, with contributions from RD, CP, and XC. LR and CP acquired the funds.

Competing interests. The contact author has declared that none of the authors has any competing interests.

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References

Ambrosini, R., Azzoni, S. R., Pittino, F., Diolaiuti, G., Franzetti, A., and Parolini, M.: First evidence of microplastic contamination in the supraglacial debris of an alpine glacier, Environnemental Pollution, 253, 297–301, https://doi.org/10.1016/j.envpol.2019.07.005, 2019.

Arienzo, M. M., Legrand, M., Preunkert, S., Stohl, A., Chellman, N., Eckhardt, S., Gleason, K. E., and McConnell, J. R.: Alpine ice-core evidence of a large increase in vanadium and molybdenum pollution in Western Europe during the 20th century, Journal of Geophysical Research: Atmospheres, 126, e2020JD033211, https://doi.org/10.1029/2020JD033211, 2021.

Bentley, C. R., Koci, B. R., Augustin, L. J.-M., Bolsey, R. J., Green, J. A., Kyne, J. D., Lebar, D. A., Mason, W. P., Shturmakov, A. J., Engelhardt, H. F., Harrison, W. D., Hecht, M. H., and Zagorodnov, V.: Ice drilling and coring, in: Drilling in extreme environments, edited by: Bar-Cohen, Y. and Zacny, K., Wiley, 221–308, https://doi.org/10.1002/9783527626625.ch4, 2009.

Bohleber, P.: Alpine ice cores as climate and environmental archives, Oxford Research Encyclopedia of Climate Science, https://doi.org/10.1093/acrefore/9780190228620.013.743, 2019.

Bohleber, P., Hoffmann, H., Kerch, J., Sold, L., and Fischer, A.: Investigating cold based summit glaciers through direct access to the glacier base: a case study constraining the maximum age of Chli Titlis glacier, Switzerland, The Cryosphere, 12, 401–412, https://doi.org/10.5194/tc-12-401-2018, 2018.

Brad, T., Itcus, C., Pascu, M. D., Per?oiu, A., Hillebrand-Voiculescu, A., Iancu, L., and Purcarea, C.: Fungi in perennial ice from Scărișoara Ice Cave (Romania), Scientific Reports, 8, 10096, https://doi.org/10.1038/s41598-018-28401-1, 2018.

Brook, E. J. and Buizert, C.: Antarctic and global climate history viewed from ice cores, Nature, 558, 200–208, https://doi.org/10.1038/s41586-018-0172-5, 2018.

Brugger, S. O., Schwikowski, M., Gobet, E., Schwörer, C., Rohr, C., Sigl, M., Henne, S., Pfister, C., Jenk, T. M., Henne, P. D., and Tinner, W.: Alpine glacier reveals ecosystem impacts of Europe's prosperity and peril over the last millennium, Geophysical Research Letters, 48, e2021GL095039, https://doi.org/10.1029/2021GL095039, 2021.

Chung, A., Parrenin, F., Mulvaney, R., Vittuari, L., Frezzotti, M., Zanutta, A., Lilien, D. A., Cavitte, M. G. P., and Eisen, O.: Age, thinning and spatial origin of the Beyond EPICA ice from a 2.5D ice flow model, The Cryosphere, 19, 4125–4140, https://doi.org/10.5194/tc-19-4125-2025, 2025.

Cremona, A., Huss, M., Landmann, J. M., Borner, J., and Farinotti, D.: European heat waves 2022: contribution to extreme glacier melt in Switzerland inferred from automated ablation readings, The Cryosphere, 17, 1895–1912, https://doi.org/10.5194/tc-17-1895-2023, 2023.

Delmas, R. J.: Environmental information from ice cores, Reviews of Geophysics, 30, 1–21, https://doi.org/10.1029/91RG02725, 1992.

Eichler, A., Legrand, M., Jenk, T. M., Preunkert, S., Andersson, C., Eckhardt, S., Engardt, M., Plach, A., and Schwikowski, M.: Consistent histories of anthropogenic western European air pollution preserved in different Alpine ice cores, The Cryosphere, 17, 2119–2137, https://doi.org/10.5194/tc-17-2119-2023, 2023.

EPICA community members: Eight glacial cycles from an Antarctic ice core, Nature, 429, 623–628, https://doi.org/10.1038/nature02599, 2004.

Feurdean, A., Perşoiu, A., Pazdur, A., and Onac, B. P.: Evaluating the palaeoecological potential of pollen recovered from ice in caves: a case study from Scărişoara Ice Cave, Romania, Review of Palaeobotany and Palynology, 165, 1–10, https://doi.org/10.1016/j.revpalbo.2011.01.007, 2011.

Gabrieli, J. and Barbante, C.: The Alps in the age of the Anthropocene: the impact of human activities on the cryosphere recorded in the Colle Gnifetti glacier, Rendiconti Lincei, Scienze Fisiche e Naturali, 25, 71–83, https://doi.org/10.1007/s12210-014-0292-2, 2014.

Gabrielli, P., Barbante, C., Bertagna, G., Bertó, M., Binder, D., Carton, A., Carturan, L., Cazorzi, F., Cozzi, G., Dalla Fontana, G., Davis, M., De Blasi, F., Dinale, R., Dragà, G., Dreossi, G., Festi, D., Frezzotti, M., Gabrieli, J., Galos, S. P., Ginot, P., Heidenwolf, P., Jenk, T. M., Kehrwald, N., Kenny, D., Magand, O., Mair, V., Mikhalenko, V., Lin, P. N., Oeggl, K., Piffer, G., Rinaldi, M., Schotterer, U., Schwikowski, M., Seppi, R., Spolaor, A., Stenni, B., Tonidandel, D., Uglietti, C., Zagorodnov, V., Zanoner, T., and Zennaro, P.: Age of the Mt. Ortles ice cores, the Tyrolean Iceman and glaciation of the highest summit of South Tyrol since the Northern Hemisphere Climatic Optimum, The Cryosphere, 10, 2779–2797, https://doi.org/10.5194/tc-10-2779-2016, 2016.

Gibson, C. J., Johnson, J. A., Shturmakov, A. J., Mortensen, N. B., and Goetz, J. J.: Replicate ice-coring system architecture: mechanical design, Annals of Glaciology, 55, 165–172, https://doi.org/10.3189/2014AoG68A019, 2014.

Guillet, G. and Ravanel, L.: Variations in surface area of six ice aprons in the Mont-Blanc massif since the Little Ice Age, Journal of Glaciology, 66, 777–789, https://doi.org/10.1017/jog.2020.46, 2020.

Guillet, G., Preunkert, S., Ravanel, L., Montagnat, M., and Friedrich, R.: Investigation of a cold-based ice apron on a high-mountain permafrost rock wall using ice texture analysis and micro-14C dating: a case study of the Triangle du Tacul ice apron (Mont Blanc massif, France), Journal of Glaciology, 67, 1205–1212, https://doi.org/10.1017/jog.2021.65, 2021.

Haeberli, W., Frauenfelder, R., Kääb, A., and Wagner, S.: Characteristics and potential climatic significance of "miniature ice caps" (crest- and cornice-type low-altitude ice archives), Journal of Glaciology, 50, 129–136, https://doi.org/10.3189/172756504781830330, 2004.

Heucke, E.: A light portable steam-driven ice drill suitable for drilling holes in ice and firn, Geografiska Annaler A, 81, 603–609, https://doi.org/10.1111/1468-0459.00088, 1999.

Hoffmann, H., Friedrich, R., Kromer, B., and Fahrni, S.: Status report: implementation of gas measurements at the MAMS 14C AMS facility in Mannheim, Germany, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 410, 184–187, https://doi.org/10.1016/j.nimb.2017.08.018, 2017.

Hoffmann, H., Preunkert, S., Legrand, M., Leinfelder, D., Bohleber, P., Friedrich, R., and Wagenbach, D.: A new sample preparation system for micro-14C dating of glacier ice with a first application to a high alpine ice core from Colle Gnifetti (Switzerland), Radiocarbon, 60, 517–533, https://doi.org/10.1017/RDC.2017.99, 2018.

Holmlund, P., Onac, B. P., Hansson, M., Holmgren, K., Mörth, M., Nyman, M., and Perşoiu, A.: Assessing the palaeoclimate potential of cave glaciers: the example of the scarişoara ice cave (romania), Geografiska Annaler: Series A, Physical Geography, 87, 193–201, https://doi.org/10.1111/j.0435-3676.2005.00252.x, 2005.

Huber, C. J., Eichler, A., Mattea, E., Brütsch S., Jenk T. M., Gabrieli J., Barbante C., and Schwikowski M.: High-altitude glacier archives lost due to climate change-related melting, Nature Geoscience, 17, 110–113, https://doi.org/10.1038/s41561-023-01366-1, 2024.

Jenk, T. M., Szidat, S., Schwikowski, M., Gäggeler, H. W., Brütsch, S., Wacker, L., Synal, H.-A., and Saurer, M.: Radiocarbon analysis in an Alpine ice core: record of anthropogenic and biogenic contributions to carbonaceous aerosols in the past (1650–1940), Atmos. Chem. Phys., 6, 5381–5390, https://doi.org/10.5194/acp-6-5381-2006, 2006.

Jenk, T. M., Szidat, S., Bolius, D., Sigl, M., Gäggeler, H. W., Wacker, L., Ruff, M., Barbante, C., Boutron, C. F., and Schwikowski, M.: A novel radiocarbon dating technique applied to an ice core from the Alps indicating late Pleistocene ages, Journal of Geophysical Research: Atmospheres, 114, https://doi.org/10.1029/2009JD011860, 2009.

Jouzel, J. and Masson-Delmotte, V.: Deep ice cores: the need for going back in time, Quaternary Science Reviews, 29, 3683–3689, https://doi.org/10.1016/j.quascirev.2010.10.002, 2010a.

Jouzel, J. and Masson-Delmotte, V.: Paleoclimates: what do we learn from deep ice cores?, WIREs Climate Change, 1, 654–669, https://doi.org/10.1002/wcc.72, 2010b.

Jouzel, J., Alley, R. B., Cuffey, K. M., Dansgaard, W., Grootes, P., Hoffmann, G., Johnsen, S. J., Koster, R. D., Peel, D., Shuman, C. A., Stievenard, M., Stuiver, M., and White, J.: Validity of the temperature reconstruction from water isotopes in ice cores, Journal of Geophysical Research, 102, 26471–26487, https://doi.org/10.1029/97JC01283, 1997.

Kaufman, D. S. and Broadman, E.: Revisiting the Holocene global temperature conundrum, Nature, 614, 425–435, https://doi.org/10.1038/s41586-022-05536-w, 2023.

Kaushik, S., Ravanel, L., Magnin, F., Yan, Y., Trouve, E., and Cusicanqui, D.: Effects of topographic and meteorological parameters on the surface area loss of ice aprons in the Mont Blanc massif (European Alps), The Cryosphere, 16, 4251–4271, https://doi.org/10.5194/tc-16-4251-2022, 2022.

Lamothe, A., Akers, P. D., Albertin S., Caillon, N., Darfeuil, S., Gautier, E., Ginot, P., Hattori, S., and Savarino, J.: 1000 years of nitrogen oxide sources in Western Europe: evidence from nitrogen stable isotopes (δ15N) of nitrate in a Mont Blanc ice core, ESS Open Archive, 8 June, https://doi.org/10.22541/essoar.171781204.49551149/v1, 2024.

Legrand, M. and Mayewski, P.: Glaciochemistry of polar ice cores: a review, Reviews of Geophysics, 35, 219–243, https://doi.org/10.1029/96RG03527, 2017.

Legrand, M., McConnell, J. R., Preunkert, S., Bergametti, G., Chellman, N. J., Desboeufs, K., Plach, A., Stohl, A., and Eckhardt, S.: Thallium pollution in Europe over the twentieth century recorded in Alpine ice: contributions from coal burning and cement production, Geophysical Research Letters, 49, e2022GL098688, https://doi.org/10.1029/2022GL098688, 2022.

Luongo, M. T., Kurbatov, A. V., Erhardt, T., Mayewski, P. A., McCormick, M., More, A. F., Spaulding, N. E., Wheatley, S. D., Yates, M. G., and Bohleber, P. D.: Possible Icelandic tephra found in European Colle Gnifetti glacier, Geochemistry, Geophysics, Geosystems, 18, 3904–3909, https://doi.org/10.1002/2017GC007022, 2017.

Maggi, V., Villa, S., Finizio, A., Delmonte, B., Casati, P., and Marino, F.: Variability of anthropogenic and natural compounds in high altitude-high accumulation alpine glaciers, Hydrobiologia, 562, 43–56, https://doi.org/10.1007/s10750-005-1804-y, 2006.

Magnin, F., Brenning, A., Bodin, X., Deline, P., and Ravanel, L.: Statistical modelling of rock wall permafrost distribution: application to the Mont Blanc massif, Géomorphologie, 21, 145–162, https://doi.org/10.4000/geomorphologie.10965, 2015.

Mariani, I., Eichler, A., Jenk, T. M., Brönnimann, S., Auchmann, R., Leuenberger, M. C., and Schwikowski, M.: Temperature and precipitation signal in two Alpine ice cores over the period 1961–2001, Clim. Past, 10, 1093–1108, https://doi.org/10.5194/cp-10-1093-2014, 2014.

Montagnat, M., Weiss, J., Cinquin-Lapierre, B., Labory, P. A., Moreau, L., Damilano, F., and Lavigne, D.: Waterfall ice: formation, structure and evolution, Journal of Glaciology, 56, 225–234, https://doi.org/10.3189/002214310791968412, 2010.

Motoyama, H.: The Second Deep Ice Coring Project at Dome Fuji, Antarctica, Scientific Drilling, 5, 41–43, https://doi.org/10.2204/iodp.sd.5.05.2007, 2007.

Mourey, J., Marcuzzi, M., Ravanel, L., and Pallandre, F.: Effects of climate change on high Alpine mountain environments: Evolution of mountaineering routes in the Mont Blanc massif (Western Alps) over half a century, Arctic, Antarctic, and Alpine Research, 51, 176–189, https://doi.org/10.1080/15230430.2019.1612216, 2019.

Müller-Tautges, C., Eichler, A., Schwikowski, M., Pezzatti, G. B., Conedera, M., and Hoffmann, T.: Historic records of organic compounds from a high Alpine glacier: influences of biomass burning, anthropogenic emissions, and dust transport, Atmos. Chem. Phys., 16, 1029–1043, https://doi.org/10.5194/acp-16-1029-2016, 2016.

Perşoiu, A., Onac, B. P., Wynn, J. G., Bojar, A.-V., and Holmgren, K.: Stable isotope behavior during cave ice formation by water freezing in Scărişoara Ice Cave, Romania, Journal of Geophysical Research – Atmospheres, 116, https://doi.org/10.1029/2010JD014477, 2011.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E., and Stievenard, M.: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, Nature, 399, 429–436, https://doi.org/10.1038/20859, 1999.

Preunkert, S. and Legrand, M.: Towards a quasi-complete reconstruction of past atmospheric aerosol load and composition (organic and inorganic) over Europe since 1920 inferred from Alpine ice cores, Clim. Past, 9, 1403–1416, https://doi.org/10.5194/cp-9-1403-2013, 2013.

Preunkert, S., Wagenbach, D., Legrand, M., and Vincent, C.: Col du Dome (Mt. Blanc Massif, French Alps) suitability for ice core studies in relation with past atmospheric chemistry over Europe, Tellus B: Chemical and Physical Meteorology, 52, 993–1012, https://doi.org/10.3402/tellusb.v52i3.17081, 2000.

Preunkert, S., Legrand, M., Kutuzov, S., Ginot, P., Mikhalenko, V., and Friedrich, R.: The Elbrus (Caucasus, Russia) ice core record – Part 1: reconstruction of past anthropogenic sulfur emissions in south-eastern Europe, Atmos. Chem. Phys., 19, 14119–14132, https://doi.org/10.5194/acp-19-14119-2019, 2019a.

Preunkert, S., McConnell, J. R., Hoffmann, H., Legrand, M., Wilson, A. I., Eckhardt, S., Stohl, A., Chellman, N. J., Arienzo, M. M., and Friedrich, R.: Lead and antimony in basal ice from Col du Dome (French Alps) dated with radiocarbon: a record of pollution during antiquity, Geophysical Research Letters, 46, 4953–4961, https://doi.org/10.1029/2019GL082641, 2019b.

Rabatel, A., Letréguilly, A., Dedieu, J.-P., and Eckert, N.: Changes in glacier equilibrium-line altitude in the western Alps from 1984 to 2010: evaluation by remote sensing and modeling of the morpho-topographic and climate controls, The Cryosphere, 7, 1455–1471, https://doi.org/10.5194/tc-7-1455-2013, 2013.

Ravanel, L., Guillet, G, Kaushik, S, Preunkert, S., Malet, E., Magnin, F., Trouvé, E., Montagnat, M., Yan, Y., and Deline, P.: Ice aprons on steep high-alpine slopes: insights from the Mont-Blanc massif, Western Alps, Journal of Glaciology, 69, 1275–1291, https://doi.org/10.1017/jog.2023.15, 2023.

Ravanel, L., Flinois, G., Jaillet, S., Malet, E., Magnin, F., Rigal, D., Burnet, H., and Hobléa, F.: Underground ice beyond the limits of the cryosphere. Glaciological functioning and uses of the Grande Glacière du Parmelan (Bornes massif, France), Géomorphologie, 30, https://doi.org/10.4000/13569, 2024.

Robin, G. D. Q.: Ice cores and climatic change, Philosophical Transactions of the Royal Society B, 280, 143–168, https://doi.org/10.1098/rstb.1977.0103, 1977.

Schöner, W., Auer, I., Böhm, R., Keck, L., and Wagenbach, D.: Spatial representativity of air-temperature information from instrumental and ice-core-based isotope records in the European Alps, Annals of Glaciology, 35, 157–161, https://doi.org/10.3189/172756402781816717, 2002.

Stoffel, M., Luetscher, M., Bollschweiler, M., and Schlatter, F.: Evidence of NAO control on subsurface ice accumulation in a 1200 yr old cave-ice sequence, St. Livres ice cave, Switzerland, Quaternary Research, 72, 16–26, https://doi.org/10.1016/j.yqres.2009.03.002, 2009.

Tison, J.-L., Souchez, R., Wolff, E. W., Moore, J. C., Legrand, M. R., and de Angelis, M.: Is a periglacial biota responsible for enhanced dielectric response in basal ice from the Greenland Ice Core project ice core?, Journal of Geophysical Research: Atmospheres, 103, 18885–18894, https://doi.org/10.1029/98JD01107, 1998.

Uglietti, C., Zapf, A., Jenk, T. M., Sigl, M., Szidat, S., Salazar, G., and Schwikowski, M.: Radiocarbon dating of glacier ice: overview, optimisation, validation and potential, The Cryosphere, 10, 3091–3105, https://doi.org/10.5194/tc-10-3091-2016, 2016.

Vimeux, F., Ginot, P., Schwikowski, M., Vuille, M., Hoffmann, G., Thompson, L. G., and Schotterer, U.: Climate variability during the last 1000 years inferred from Andean ice cores: A review of methodology and recent results, Palaeogeography, Palaeoclimatology, Palaeoecology, 281, 229–241, https://doi.org/10.1016/j.palaeo.2008.03.054, 2009.

Xu, J., Hou, S., Qin, D., Kaspari, S., Mayewski, P. A., Petit, J. R., Delmonte, B., Kang, S., Ren, J., Chappellaz, J., and Hong, S.: A 108.83-m ice-core record of atmospheric dust deposition at Mt. Qomolangma (Everest), Central Himalaya, Quaternary Research, 73, 33–38, https://doi.org/10.1016/j.yqres.2009.09.005, 2010.

Xu, C. H., LI, Z. Q., Wang, F. T., Wang, P. Y., and Mu, J. X.: Rapid mass loss and disappearance of summer-accumulation type hanging glacier, Advances in Climate Change Research, 13, 73–81, https://doi.org/10.1016/j.accre.2021.11.001, 2021.

Zhang, N., An, C., Fan, X., Shi, G., Li, C., Liu, J., Hu, Z., Talalay, P., Sun, Y., and Li, Y.: Chinese first deep ice-core drilling project DK-1 at Dome A, Antarctica (2011–2013): progress and performance, Annals of Glaciology, 55, 88–98, https://doi.org/10.3189/2014AoG68A006, 2014.

Zagorodnov, V., Thompson, L. G., Ginot, P., and Mikhalenko, V.: Intermediate-depth ice coring of high-altitude and polar glaciers with a lightweight drilling system, Journal of Glaciology, 51, 491–501, https://doi.org/10.3189/172756505781829269, 2005.