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Late Holocene evolution of the Adamello Glacier (Rhaetian Alps): New insights for Alpine temperate glaciers

Abstract: Maggi V., Salvatore M.C., Casarotto C., Mangili C., Carton A., Baccolo G., Brugger S.O., Jenk T.M., Eichler A., Schwikowski M., Baroni C., *Late Holocene evolution of the Adamello Glacier (Rhaetian Alps): New insights for Alpine temperate glaciers.* (IT ISSN 0391-9838, 2023). The Adamello Glacier is the largest and the thickest glacier in the Italian Alps, with a maximum ice thickness of 270 m. Here we provide an overview of its evolution since the Little Ice Age and of the results obtained from the ice core drilling activities carried out on this glacier. A review of the existing cartography from the 19th century onwards, surveys by the Italian Glaciological Committee, geomorphological studies and mass balance data are here combined to quantitatively describe the evolution of the Adamello Glacier from the Little Ice Age to the present day. Within this interval, the glacier has lost half of its surface, and its main front has receded by 2.8 km. Despite the rapid decline, in the last years ice cores were extracted from the former accumulation area of the glacier (Pian di Neve). In 2021, a 224 m-long ice core was drilled to bedrock. We also consider a previous ice core (ADA16), drilled in 2016 to the depth of 46 m. The analysis and inspection of these ice cores show that, despite the glacier consist of temperate ice and is subject to severe melting, some environmental signals are partially preserved in the ice stratigraphy, including visible layers related to Saharan dust transport and cryoconite. Using information from the upper layers of the glacier and a one-dimensional age-depth model, it was possible to estimate the age of the basal ice at approximately 2000 years ago. According to these preliminary results, the Adamello Glacier, despite being a temperate glacier and being subject to heavy melting during summer, is still able to preserve, at least partially, signals that are suitable to construct climatic and environmental records. This implies that, contrary to the previous view, environmental records can be obtained from ice cores drilled at temperate glaciers subject to melting. In the context of climate change, this is a relevant result with important implications for paleoclimatic and environmental reconstructions.

Key words: Temperate glaciers, glacier variation, ice cores, paleoclimate, Little Ice Age, Holocene, Rhaetian Alps.

Riassunto: Maggi V., Salvatore M.C., Casarotto C., Mangili C., Carton A., Baccolo G., Brugger S.O., Jenk T.M., Eichler A., Schwikowski M., Baroni C., *Evoluzione tardo-olocenica del Ghiacciaio dell'Adamello (Alpi Retiche): nuove conoscenze sui ghiacciai temperati alpini.* (IT ISSN 0391-9838, 2023). Il ghiacciaio dell'Adamello è il più esteso delle Alpi italiane, con uno spessore massimo misurato di circa 270 m. In questo lavoro viene presentata una panoramica dell'evoluzione di questo ghiacciaio a partire dalla Piccola Età Glaciale. Sono inoltre presentati i risultati preliminari dalle attività di carotaggio che hanno coinvolto il ghiacciaio dell'Adamello. Combinando la revisione della cartografia esistente a partire dal XIX secolo, le campagne annuali del Comitato Glaciologico Italiano, gli studi geomorfologici e i dati del bilancio di massa, è stata ricostruita in modo quantitativo l'evoluzione del ghiacciaio dell'Adamello dalla Piccola Età Glaciale a oggi. In questo arco temporale, il ghiacciaio ha perso metà della sua superficie e la sua fronte principale si è ritirata di 2.8 km. Nonostante il rapido declino, negli ultimi anni sono state estratte carote di ghiaccio dall' area di accumulo del Pian di Neve. Nel 2021 è stata effettuata una perforazione che ha raggiunto il substrato roccioso, permettendo l'estrazione di una carota di ghiaccio lunga 224 m. In questo lavoro consideriamo anche i dati ottenuti da un precedente carotaggio (ADA16). L'analisi di tali carote ha mostrato che, nonostante

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il ghiacciaio sia in condizioni temperate e sia soggetto a forte fusione, alcuni segnali ambientali sono parzialmente conservati nella stratigrafia del ghiaccio, compresi alcuni livelli legati al trasporto di polvere sahariana e all'accumulo di crioconite. Utilizzando le informazioni provenienti dagli strati superiori del ghiacciaio e un modello di età-profondità monodimensionale, è stato possibile stimare l'età del ghiaccio basale, che risalirebbe a circa 2000 anni fa. Secondo questi risultati preliminari, il ghiacciaio dell'Adamello, pur essendo un ghiacciaio temperato e soggetto a forte fusione estiva, è in grado di conservare, almeno in parte, dei segnali adatti alla costruzione di record climatici e ambientali. Ciò implica che, contrariamente a quanto ritenuto in precedenza, sia possibile ottenere dati significativi da carote di ghiaccio estratte da ghiacciai temperati. Nel contesto del cambiamento climatico, questo è un risultato rilevante con importanti ricadute per le ricostruzioni paleoclimatiche e ambientali.

Termini chiave: Ghiacciai temperati, variazioni glaciali, perforazioni in ghiaccio, paleoclima, Piccola Età Glaciale, Olocene, Alpi Retiche.

INTRODUCTION

The dramatic withdrawal of glaciers induced by the ongoing climate warming is widely observed and documented on mountain areas all over our planet (Zemp *et al.*, 2015; Sommer *et al.*, 2020; IPCC, 2007, 2023; WGMS, 2023). When compared to present day, recent global glacier projections indicate a significant mass loss by 2100, estimated in ca. 26% to 41%, when considering global temperature change scenarios of +1.5 °C and +4 °C, respectively (Rounce *et al.*, 2023).

In the Alps, since the last significant Holocene advance of the Little Ice Age (LIA, ca. 1850), glaciers are experiencing a progressive retreat and contraction that dramatically accelerated after the end of the 20th century (IPCC, 2007, 2023; Brunetti *et al.*, 2009; Büntgen *et al.*, 2011; Sommer *et al.*, 2020).

In the Italian sector of the Alps, since 1957 (when the first thorough inventory of Italian glaciers was compiled; CGI-CNR, 1959, 1961a, 1961b, 1962), glaciers have been experiencing a strong areal reduction, with the last positive fluctuation occurring in the late '70s and early '80s of the last century. The comparison of the conditions of Italian glaciers in the hydrological year 1957-1958 and in the hydrologic year 2006-2007 revealed that, as a consequence of areal and volumetric reductions, they underwent a progressive fragmentation into smaller bodies, leading to an increase in glacier total number (Salvatore *et al.*, 2015). Under the ongoing trend of glacier shrinkage, fragmentation has quickened the melting and brought to the extinction of an increasing number of glacial bodies. Severe retreat and mass loss are also affecting the largest Italian glaciers, which are recording increasingly negative mass balance (CGI 1928-1977, CGI 1978-2017; Baroni *et al.*, 2018, 2019, 2020a, 2020b, 2022, 2023). The progressive surface lowering of glaciers has consequences both in terms of "water tower" reduction, and of loss of environmental data preserved in ice (Zhang *et al.*, 2015). Through ice cores, glaciers and ice caps of mid-latitude high mountain ranges provide climate records that are complementary to the ones retrieved from the polar regions (Thompson, 2014). Under the ongoing climate warming, collecting ice cores taken from vanishing glaciers is crucial in order to preserve the valuable archive of our climate and environment history recorded in glacial bodies. In this light, the Ice Memory project acts to preserve and store ice cores from Earth's mountain glaciers in Antarctica (https://www.ice-memory.org/english/, last access August 2024). Compared to polar contexts, mountain regions are characterised by smaller glaciers located in the proximity of densely populated and industrialised regions. As such, glaciers from mid-latitude ranges have been invaluable in providing climatic and environmental records highlighting human impacts on the atmosphere (Beaudon *et al.*, 2017; Eichler *et al.*, 2023). In the European Alps, ice core studies have been performed at the few sites presenting accumulation basins characterised by cold thermal conditions (i.e., firn and ice temperature consistently below the pressure melting point). These include Col du Dôme, Mont Blanc (Preunkert *et al.*, 2000), Fiescherhorn, Bernese Alps (Schwerzmann *et al.*, 2006), Ortles, Eastern Alps (Gabrielli *et al.*, 2016), as well as Colle Gnifetti and Colle del Lys in the Monte Rosa region (e.g., Wagenbach *et al.*, 2012, and references therein; see fig. 1 for location). These are the only sites where a cold thermal state is found in association with conditions favourable for ice core drilling: flat topography, preservation of the original stratigraphy, no influence from avalanches. Apart from the aforementioned sites, the other cold glaciers in the Alps are not suitable to extract ice cores. Other glaciers of the Alps presenting suitable geometric and glaciological features have not been considered so far because the thermal state of their accumulation basins is not cold, but temperate. This means that they are at the pressure melting point and contain some liquid water. As meltwater disturbs the preservation of climatic signals, such glaciers have always been avoided for ice core drilling. In fact, melting and meltwater can disturb, or even destroy, the chemical and physical signals embedded into glacier ice (Pohjola *et al.*, 2002; Moore *et al.*, 2005; Pu *et al.*, 2020; Clifford *et al.*, 2022). On the other hand, particulate matter, such as mineral dust, pollen and black carbon, does not seem to be disturbed by meltwater at the same degree. Green algae, cyanobacteria, bacteria, fungi, and pollen can be preserved in well-defined layers at their original depth of deposition, despite meltwater inclusions (e.g., Nakazawa *et al.*, 2004; Uetake *et al.*, 2006; Festi *et al.*, 2017). Therefore, climate and environmental records can be reconstructed using temperate ice cores by means of mineral dust, black carbon, pollen and other palynomorphs plus chemical species only partially affected by meltwater percolation (Pavlova *et al.*, 2015; Kaspari *et al.*, 2020; Festi *et al.*, 2021).

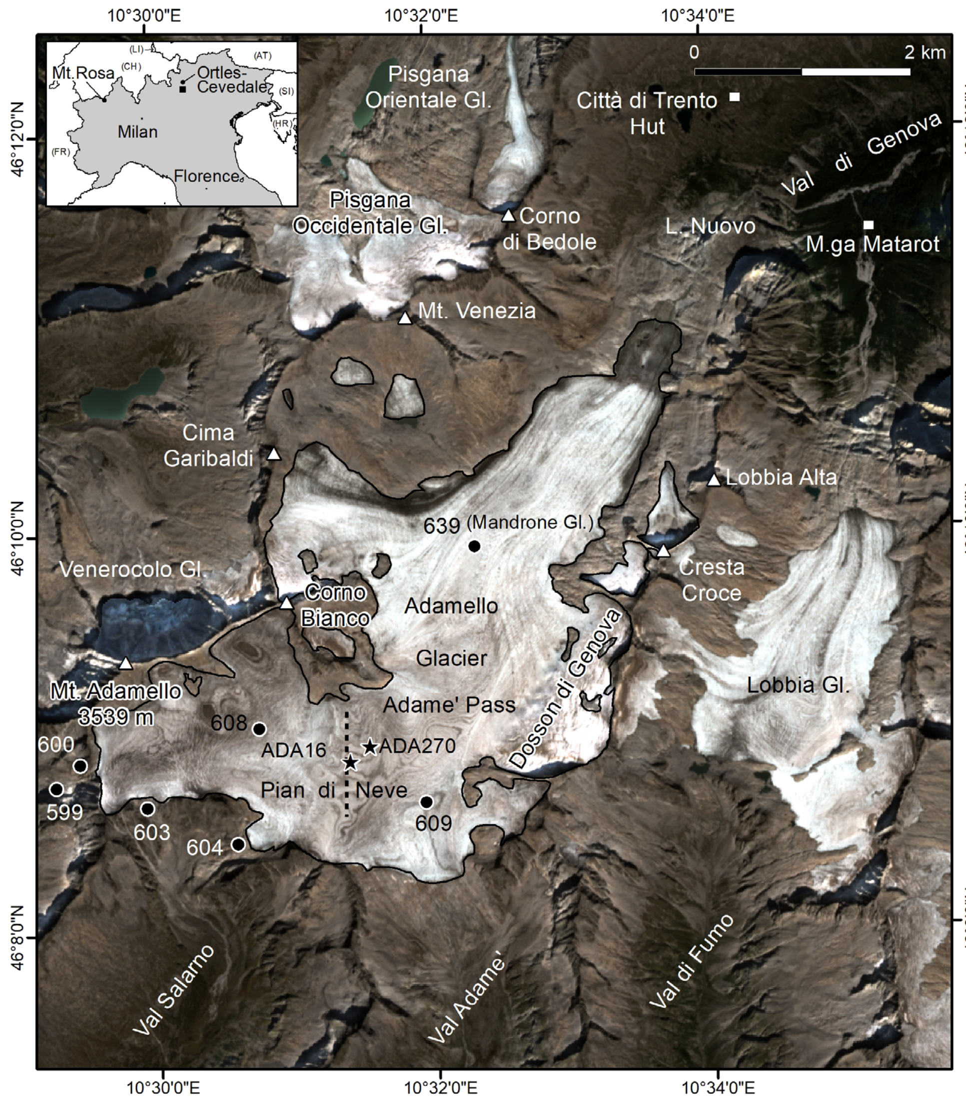

Figure 1 - Location map of the Adamello Glacier (black square in the inset). Black line outlines indicate Adamello Glacier limit in 2023; stars indicate the position of the ADA270 and ADA16 ice cores; the dotted line indicates the geophysical transect from Picotti *et al.* (2017). Black circles indicate the location (with code) of individual glacial bodies according to the Italian Glacier Inventory (CNR-CGI, 1961a, 1961b, 1962). 599: Cima del Laghetto; 600: Miller superiore; 603: Corno Salarno; 604: Salarno; 608: Adamello or Pian di Neve; 609: Adamè; 639: Mandrone. Base map: Sentinel-2 satellite image taken on 8 September 2023 (RGB-true colour composite processed using light bands red (B04), green (B03) and blue (B02)).

Climate change is now posing new issues from the ice preservation perspective, as many cold glaciers are turning to a temperate regime because of atmospheric warming (Hoelzle *et al.*, 2011; Gilbert *et al.*, 2015). As such, the ice core community is trying to improve the ability to use temperate glacier ice as a paleoclimatic archive (Schuster *et al.*, 2002; Neff *et al.*, 2012; Chellman *et al.*, 2017). Improving the ability to read and interpret paleoclimatic signals in temperate ice cores would significantly broaden the pool of drillable glaciers in the future, permitting to extract valuable information even from glaciers affected by climate change.

According to this scenario, we present here a glaciological overview of the Adamello Glacier, the largest glacier in the Italian Alps. The peculiar geometry of the Adamello Glacier and the ongoing climate warming cause the snowline to be currently often above the local orographic limit. Consequently, the glacier has now almost completely lost its accumulation basin and has negative mass balances even at its upper sectors. Melting is of course severe and involves the entire glacial mass. We present here data on the Adamello Glacier and on its evolution since the Little Ice Age (LIA) and beyond, derived from historical maps, field surveys and remote sensing data. Moreover, we outline the drilling activities and geophysical surveys carried out on the Adamello Glacier since 2015, including some preliminary results about the possibility to extract useful environmental signal from such a glacier.

THE ADAMELLO GLACIER

The Adamello Glacier (46° 09′ 02″ N, 10° 31′ 50″ E) is the widest glacial body of the Italian Alps (Baroni and Carton, 1996; Salvatore *et al.*, 2015), covering an area of 12.87 km^2 in September 2023 (this work; fig. 1). It is also the thickest glacier in Italy, with an estimated ice thickness of more than 250 m at the Pian di Neve, in its upper sectors (Frassoni *et al.*, 2001; Picotti *et al.*, 2017).

In the first Italian Glacier Inventory (CGI-CNR, 1959, 1961a, 1961b, 1962), the Adamello Glacier was described as consisting of six distinct glacial units (n. 600, 603, 604, 608, 609, 639 codes in CGI-CNR, 1961b, 1962; fig. 1). Later, it was considered as a unitary glacial body based on its morphological characteristics and glacial dynamics. In fact, the Adamello Glacier is a high plateau glacier, originally defined as "summit glacier of Scandinavian type" by Marson (1906). The glacier is located on a plateau, at an average elevation of ca. 3000 m a.s.l., and feeds (or fed) different effluences descending from the summit area (Marson, 1906; Servizio Glaciologico Lombardo, 1992; Baroni and Carton, 1996; Ranzi *et al.*, 2010; Grossi *et al.*, 2013). The World Glacier Inventory (WGI, www.wmgs.ch) considers this glacier as a compound basin valley system, grouping together all the glacier tongues on the Lombardy side (WGI code I-4L01024-06), and considers as an isolated entity the Mandrone Glacier (WGI code I-4L01011-15), whose front falls within the Trentino Region.

The Pian di Neve flows mainly along the Mandrone Glacier toward north but feeds also the Adamè and the Salarno glaciers, including some minor ice bodies located eastward and southward (fig. 1). Traditionally, the ice divide of the glacial flow channelled towards the Val di Genova (Mandrone Glacier) is placed at the Adamè Pass while the vast plateau called Pian di Neve is located to the south of the pass. This area, which represented the accumulation basin of the glacier, receives the contribution of other flows that originate both to the west (Corno Bianco sector) and to the east (Dosson di Genova sector). The Mandrone tongue is also fed by the northern sector of the Corno Bianco and by the glacial flows from the cirques engraved on the Lobbia ridge. Until a few years ago, the Mandrone Glacier was connected to the glacier located south of Mt. Venezia and the one hosted in the cirques between Cresta Croce and Lobbia Alta (fig. 1).

METHODS

To reconstruct the late Holocene history of the Adamello Glacier, we applied direct and indirect methods, combining field surveys and the analyses of a multitemporal dataset that include historical and geomorphological maps, stereoscopic aerial photographs, orthophotos, Digital Terrain Modell (DTM) and LiDAR data. The LIA glacial limit was reconstructed on the basis of geomorphological and glacial geological field surveys, aided by photointerpretation and existing geomorphological and historical maps (Payer, 1865; Deutschen und Österreichischen Alpen Verein, 1903; Baroni and Carton, 1988, 1996; Baroni *et al.*, 2014; Zanoner *et al.*, 2017). LiDAR data (acquired in 2014) and DTM, respectively provided by the Provincia Autonoma di Trento (https://siat.provincia.tn.it/stem/, last access August 2024) and by the Regione Lombardia (https://www.geoportale.regione.lombardia.it/, last access August 2024), were processed as hillshades to improve LIA outline interpretation. Glacier outlines in the 20th and 21st centuries were inferred as well from historical maps, multitemporal aerophotographic documents, and satellite images. Examined documents and details are listed in table 1. Historical maps edited by Italian Istituto Geografico Militare (IGM) and Deutschen und Österrechischen Alpenverein (DÖAV) are personal acquisitions of the Authors. High-resolution multi-temporal orthophotos provided a valuable source of data for reconstructing the evolution of the Adamello Glacier. In particular, orthophotographs taken in 1988, 1994 and 2006 are available as Web Map Service (WMS) at the National Cartographic Portal (PCN, www.minambiente.it, last access August 2024), 2003 is available via WMS at Geoportale Regione Lombardia (https://www.cartografia.servizirl.it/arcgis2/services/BaseMap/ortofoto2003/ImageServer/WMSServer, last access August 2024), and 2015 is available via WMS at Geoportale Regione Lombardia (http://www.cartografia.servizirl.it/arcgis2/services/BaseMap/ortofoto2015UTM32N/ImageServer/WMSServer?, last access August 2024) and at Provincia Autonoma di Trento (http://www.territorio.provincia.tn.it/portal/server.pt/community/ortofoto_2015/1113/ortofoto_2015/439453, last access August 2024).

To improve the temporal steps, orthophotos were extracted from 1959 aerial photographs, applying a direct linear transformation to georeference the respective photograms. Finally, the most recent data are from Sentinel-2 satellite images (2020, 2022, 2023), which are freely available from the Copernicus Data Space Environment (https://dataspace.copernicus.eu/, last access August 2024). The detection of glacier outlines from historical maps and aerial photographs was validated also by means of terrestrial historical photographs taken during the annual glaciological surveys and available in the Italian Glaciological Committee archives or in local archives.

As concerns the uncertainty of the glacier boundaries, and thus the accuracy of the area value obtained, the estimated error strictly depends on the type of data used and their characteristics. The comparison between the high resolution orthophotos (pixel size $\leq 1 \times 1$ m, i.e., 1959, 1988, 1994, 2003, 2006, 2015) shows a good co-registration accuracy, with few minor residual misalignments in places at the highest elevation in correspondence of the main peaks. The digitizing error is relatively small with an estimated value of less than ±2%, assessed following Vögtle and Schilling (1999). As regards the glacier outlines detected by the Sentinel-2 images, although these satellite images exhibit a spatial resolution lower than the orthophotos (10×10 m Vs $\leq 1 \times 1$ m), the comparison of the Adamello Glacier main body area value measured by the two different data sources in a test year (2015) showed a difference of less than 0.5%, which is certainly acceptable for the reconstruction of the glacier evolution.

The frontal variations of the Adamello Glacier were reconstructed by means of a time-distance curve obtained from a set of validated frontal measurements taken since the early 20th century visits to the northern tongue of the glacier (Mandrone Glacier auct.; Merciai 1920, 1921a, 1921b, 1925;) and during the glaciological annual surveys coordinated by CGI (CGI 1928-1977; CGI, 1978-2017; Baroni *et al.*, 2018, 2019, 2020a 2020b, 2022, 2023). Although measurements of frontal variations are discontinuous and were repeatedly interrupted (e.g., during the I and II World Wars), data supplied by annual glaciological surveys cover a long-time interval, spanning from 1919 to present. In this work, we implemented the time-distance curve by integrating and validating measurements from the annual glaciological surveys with data obtained from the position reached by the frontal margin during the maximum expansion of the LIA, the position provided by selected georeferenced historical maps and by aerophotographic documents.

Mass balance data derives from glaciological campaigns conducted since 2008 by the Provincia Autonoma di Trento (PAT), Muse Science Museum and Società degli Alpinisti Tridentini (SAT). Data are available on Meteotrentino web page (https://shorturl.at/E9brC, last access February 2024), and since 2018 yearly published as part of the Annual glaciological survey of Italian glaciers of CGI (in Baroni *et al.*, 2018, 2019, 2020a, 2020b, 2022, 2023). The mass balance was inferred combining direct measurements of both accumulation and ablation at winter snow sounding points and ablatometric stakes. Observations were conducted considering a wide part of the glaciers, distributing the measurements points over different sectors and elevations (fig. 2).

Other data of variations in glacier surface elevation derive from Real Time Kinematic geodetic survey conducted in 2016 and 2020 by PAT, Muse and SAT, adopting a survey technique in agreement with those commonly adopted (e.g., Eiken *et al.*, 1997; Gandolfi *et al.*, 1997; Beedle *et al.*, 2014). The measurements were obtained using two differential GPS receivers (Leica GPS SYSTEM 1200), with a fixed base placed at Cima Cresta Croce (also known as Punta Giovanni Paolo II), while the rover carried by an operator surveyed significant sectors of the glacier and the same points where the snowpack was probed for the determination of the winter balance by the direct method (fig. 2). The accuracy provided by the rover-based system has enabled the altitude measurements at the same point to be repeated with centimetric precision.

Preliminary data about the ionic impurities present in fresh winter snow and in the top-most layers of the ADA270 ice core (drilled at Pian di Neve in April 2021, fig. 1) were gathered at the Paul Scherrer Institut. Snow and ice samples were stored at -25°C and cut in 10 cm pieces and the outer part was mechanically removed with a clean band-saw. Decontaminated samples were placed in ultra-cleaned plastic tubes and melted. Major ions (Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}) were analysed through ion chromatography (850 Professional IC equipped with a 872 Extension Liquid Handling and a 858 Professional Sample Processor auto sampler, Metrohm, Herisau, Switzerland). Cations and anions were separated using Metrosp C4 and A Supp 10 columns respectively (Metrohm); 15 external standards (with a concentration ranging from 2 to 1000 ng g^{-1}) were used to build calibration curves. Blanks were prepared with ultra-pure water (18 MΩ cm^{-1} quality, Milli-Q® Element, Merck Millipore, Burlington, MA, USA) to determine detection limits and monitor the laboratory background. During analyses, the potential instrumental drift was assessed through the repeated measurement of an in-house standard (measured every twentieth sample). The overall precision of the method was ~5%. Further details can be found in Avak *et al.* (2019).

The one-dimensional Dansgaard-Johnsen ice-flow model (Dansgaard and Johnsen, 1969) was used to calculate the depth-age relationship at the ADA270 drilling site coordinates. The Dansgaard-Johnsen model employs a straightforward piecewise-linear representation of the horizontal-velocity profile, presumed to maintain a constant velocity matching the surface velocity, down to a fixed distance (the shear zone) above the bed (Neff *et al.*, 2012).

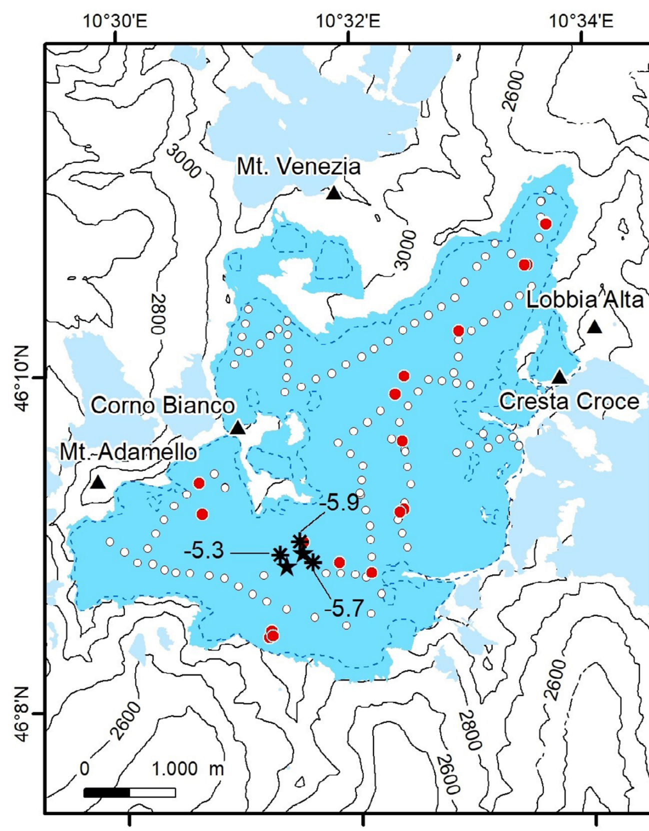

Figure 2 - Location of ablatometric stakes (red dots), GPS measurement points and snowpack soundings (white dots). Cyano area represents Adamello Glacier in 2006 (Salvatore *et al.*, 2015), the dashed line indicates glacier outline in September 2022 (this work). The asterisks indicate the geodetic survey points closest to ADA16 and ADA 270 (black stars, see fig. 1 for ice cores position) with the loss of ice thickness, in metres, from 2016 to 2020.

ADAMELLO GLACIER CHANGES

The Adamello Glacier has been studied since the beginning of the 19th century. The first description of the glacier is by Payer (1865), who provided a comprehensive map of the upper Val Genova, including Pian di Neve and the Adamello Glacier plateau at a scale of 1:56,000 followed by a further map published in 1868, at a scale of 1:25,000. Suda (1879) realized a map, where the front of the Mandrone and Lobbia glaciers in 1820 appear to be welded in correspondence of "Acqua Pendente" (fig. 1). This reconstruction was drawn by the author based on verbal testimonies and is not supported by field evidence. In the same work, the Author presented another reconstruction of the glaciers reported in 1878, where he proposed the position as depicted by Payer (1865).

The first systematic studies focusing on the Adamello Glaciers date back to the early years of the 20th century, when data about the state of ice fronts and their evolution were reported (e.g., Marson, 1906, 1912; Baroni and Carton, 1996 and references therein).

The maximum position reached during the LIA (more than 25 km^2; fig. 3; table 1) was recognized by means of geomorphological and glacial geological surveys, and mapped by Baroni and Carton (1988, 1990, 1992, 1996), Baroni *et al.* (2011, 2014) and Zanoner *et al.* (2017). Well-preserved evidence of the stationing of the northern tongue of the Adamello Glacier in this period occurs on the hydrographic left, upstream of the Lago Nuovo threshold. The maximum Holocene advance of LIA is documented by a left lateral embankment reaching an elevation of about 1750 m a.s.l. and a small patch of frontal embankment near the cable car station close to the Città di Trento Hut (1690 m a.s.l.). Samples of a soil buried by fluvio-glacial pebbly deposits in this area furnish a minimum age of 410 ± 40 years B.P. (GX-18493; 1430-1635 CE cal age) for the Lobbia and Mandrone glaciers maximum Holocene advance, occurred during the first phases of the LIA, as highlighted by the section described at Malga Matarot (Baroni and Carton, 1996). The southern tongue of the Pian di Neve extended into the Adamè valley, reaching an altitude of 2230 m a.s.l., as evidence of maximum Holocene expansion preserved as moraines. On the basis of their geomorphological context, also documented by historical maps (Payer, 1865; k.u.k. Militär Geographischen Institutes, 1892; DÖAV, 1903), weathering degree, stratigraphic positions and soil characteristics, these moraines have been attributed to the LIA (Baroni *et al.*, 2014). Finally, during the LIA, a minor effluence of the Adamello Glacier descended into the head of Val Miller, reaching an elevation of about 2560 m, occupying the area hosting Miller superiore and Miller inferiore glaciers (CGI code 600 and 599, respectively).

According to IGM and DÖAV historical maps, during the second half of the 19th century, it progressively shrank, reaching an extent of ca 22.03 km^2 at the beginning of 20th century (table 1). In 1903, on the hydrographical left, the confluent glacier flowing from the elongate cirque of the Valletta separated from the main glacial body, creating a minor glacier with an extension of ca 0.5 km^2. In 1959, this minor glacier was described as a tiny ice plate nested at the higher elevations at the foot of Mt. Venezia.

Information on areal variation is lacking between 1908 and 1950. The Italian glacier inventory (CGI-CNR, 1961b, 1962) furnishes the estimated extension of about 18 km^2 for the 1957-58 hydrological year (table 1). In 1959, the glacier extended about 18.3 km^2 and slightly increased in the 1970s and 1980s (table 1), documenting the last advance period, which caused the glacier to reach a surface area of less than 19 km^2. This positive pulse was observed for many glaciers in the Alps and in other mountain areas of the northern hemisphere (Zemp *et al.*, 2008). Since then, the Adamello Glacier underwent a continuous and progressive contraction, which involved both the lower part of the tongue and the upper sectors of the glacier. The decline of the glacier accelerated in the last decade; in 2023 its area reached an extension of 12.87 km^2 for the main body (13.54 km^2 considering also six fractioned glaciers detached from the Adamello Glacier; fig. 3 and 4a; table 1). Considering only the main glacial body, the shrinkage, which has occurred from the maximum Holocene expansion (LIA) onwards, has led, to date (2023), to a loss of more than 49% of the initial glaciated area (46.5% if we consider also the detached minor glaciers).

Areal reduction is accompanied by evident frontal retreat, which is well documented by the northern effluence of the Adamello Glacier (Mandrone Glacier). The time-distance curve (fig. 4b) exhibits a strong frontal retreat of the northern glacier's margin, recording a frontal withdrawal from the LIA to the present of more than 2800 m, interrupted by periods of stasis or by short re-advance phases, which occurred during the '30s, early '40s and the late '70s of the 20th century. Since the end of the '90s of the last century, the frontal retreat strongly increased (about 500 m in 25 years from 1997 to 2022, at a rate of about 20 m a^{-1}), registering a relevant pronounced acceleration in the last decades (295 m in only 8 years, with a rate of more than 37 m a^{-1}).

Since the LIA, the Adamello Glacier has undergone a mean lowering of more than 50 m (Baroni *et al.*, 2011). During the last decades, the entire glacier has been thinning and shrinking also at the highest elevation, as made evident by the opening of rocky windows even in the accumulation basin. In the last few years, the glacier has completely lost its snow cover, even at the highest altitudes. This means that, nowadays, the glacier lies entirely below the equilibrium line. Systematic glacier mass balance measurements, conducted since the hydrological year 2007-2008, underline a significant mass loss during the last decade.

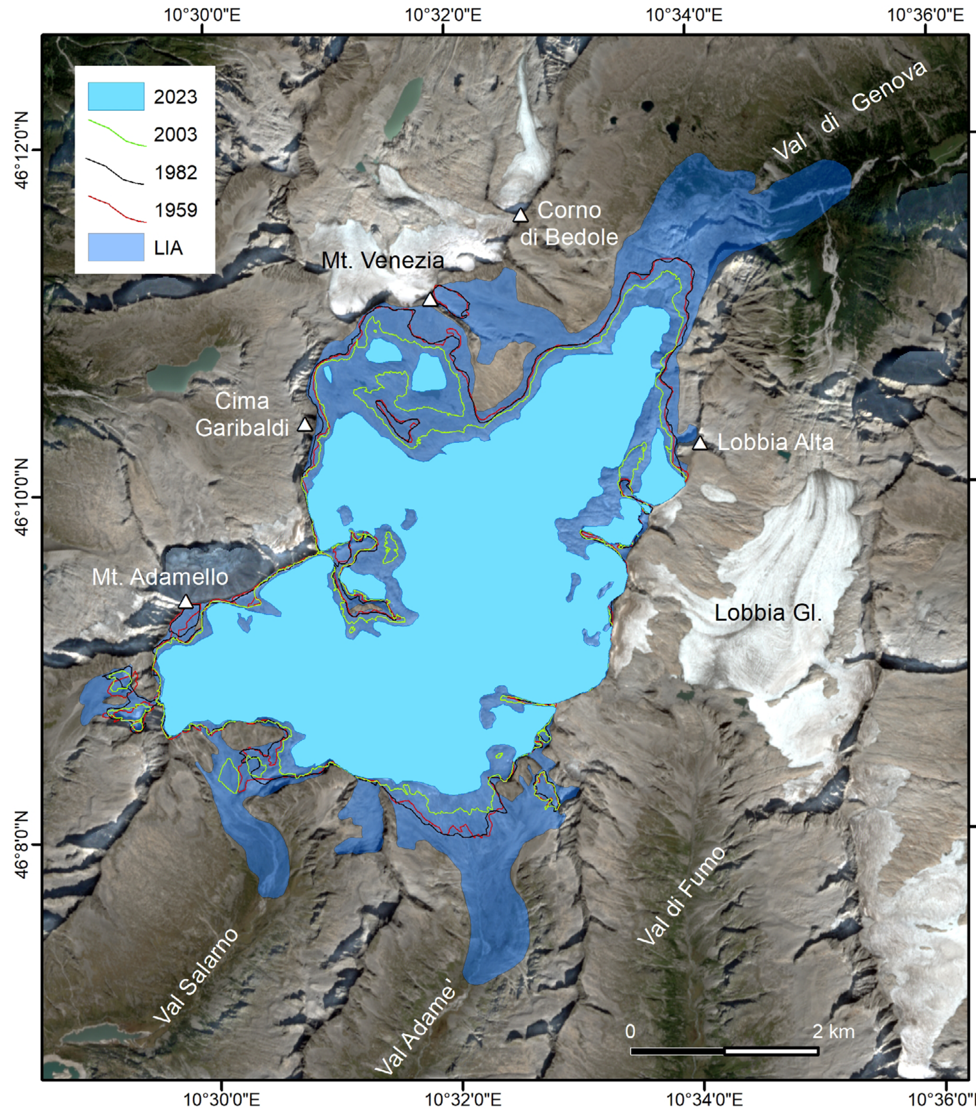

Figure 3 - The Adamello Glacier. Selected glacier outlines from the LIA maximum extension (in blue) and 2023 AD (in cyano). Intermediate positions are indicated with different colours.

Between 2007-2008 and 2021-2022, the net balance of the Adamello Glacier was markedly negative, resulting in a total loss of more than 16 m w.e. (data available at https://tinyurl.com/4zjf2hed, last access August 2024). This negative trend was interrupted by a mild positive balance recorded in 2012-13 and 2013-14, which registered the highest positive winter balance values (2.3 and 2.5 m w.e., respectively) and more contained summer balance losses (-1.9 m w.e. for both years), the less negative of the series. The most negative net balance (-3.6 m w.e.) was recorded in 2021-22 (fig. 5).

Modelled energy-mass balance estimated for the Adamello Glacier (excluding the part south of the Pian di Neve ice divide) furnishes an average water equivalent net loss of 1.3 m a^{-1} and 1.4 m a^{-1} considering the periods spanning from 1995 to 2006 and from 1995 to 2009, respectively (Ranzi *et al.*, 2010; Grossi *et al.*, 2013). Results are comparable with those obtained with the direct glaciological method for the Caresèr Glacier (Ortles-Cevedale Group; see fig. 1 for location), a relatively nearby mass balance reference glacier that has been monitored since 1966/67 by CGI for the World Glacier Monitoring Service international database (Zanon, 1992; Carturan and Seppi, 2007; Carturan *et al.*, 2013). According to the regional climate model COSMO-CLM (standing for COnsortium for Small-scale MOdeling model in CLimate Mode), future projections on the evolution of the glacier indicate that the Mandrone Glacier might not survive the current century, and its size could be halved by 2050 (Grossi *et al.*, 2013). No further studies have been published on the potential evolution of the Adamello Glacier by the end of the century. However, considering the most recent data on climate change and glacier mass loss, this projection could be expected even earlier (IPCC, 2023; Cook *et al.*, 2023). Moreover, the trends currently observed in terms of surface reduction (fig. 4) and mass balances (fig. 5) suggest that future predictions may be more pessimistic.

Table 1 - The Adamello Glacier extension (km^2) and areal change (%) from the LIA to 2023 CE. The table supplies areal extension values considering both i) the Adamello Glacier sensu stricto only (main body) and, ii) the extent of the minor glaciers originated by fractionation of the Adamello Glacier due to glacier shrinkage. Number of fractionated glaciers are in brackets (n). The areal reduction (%) respect to the LIA maximum extension is calculated considering both i) the main body only and, ii) the main body plus the areal extension of the detached smaller glaciers.

Year	Area (km^2)		Areal reduction (%)		Source of data	Data type
	main body	fractioned glaciers (n)	main body	including fractioned glaciers		
LIA	25.29	0	0.0	0.0	this work, modified after Baroni *et al.*, 2014 & Zanoner *et al.*, 2017	Field surveys, aerial photographs and LiDAR data (2014). Base map hillshade derived from LiDAR data (pixel size 0.5 × 0.5 m).
1885	24.57	0.26 (1)	-2.9	-1.8	this work	Historical maps. Istituto Geografico Militare. F 20 IV SO Temù and F 20 III NO Monte Adamello. Topographic maps at a scale of 1: 1:25,000.
1903	22.03	0.56 (2)	-12.9	-10.7	this work	Historical maps. Deutschen und Österreichischen Alpen Verein. Karte der Adamello und Presanella Gruppe. Scale: 1: 50,000.
1925	21.38	0.74 (3)	-15.5	-12.5	this work	Historical maps. Istituto Geografico Militare. F 20 IV SO Temu' and F 20 III NO Monte Adamello. Topographic maps at a scale of 1: 1:25,000.
1957	17.97	0.82 (2)	-28.9	-25.7	CGI-CNR, 1961b, 1962	Field survey. Base map topographic maps at a scale of 1:25,000.
1959	18.33	0.26 (4)	-27.5	-26.5	this work	Orthorectified aerial photograms taken on 1959 (northern tongue and part of the upper basin; pixel size 1 × 1 m); Astori and Togliatti (1964) for the Pian di Neve sector.
1970	18.70	0.50 (4)	-26.0	-24.1	this work	Map. Istituto Geografico Militare. F 058 Monte Adamello. Scale: 1:50,000.
1982	18.43	0.33 (4)	-27.1	-25.8	this work	Carta Tecnica Regionale Regione Lombardia and Carta Tecnica Provinciale Provincia Autonoma di Trento at a scale of 1: 1:10,000.
1983	18.85	n.a.	-25.5	n. a.	Maragno *et al.*, 2009	Colour aerial photographs.
1988	18.26	0.34 (6)	-27.8	-26.5	this work	Orthophotos via WMS at Geoportale Nazionale - Ministero dell'Ambiente e della Sicurezza Energetica. Pixel size 1 × 1 m.
1991	18.13	0.38 (5)	-28.3	-26.8	Servizio Glaciologico Lombardo, 1992	Field survey. Base map: Carta Tecnica Regionale Regione Lombardia at a scale of 1:10,000.
1994	17.72	0.27 (4)	-30.0	-28.9	this work	Orthophotos via WMS at Geoportale Nazionale - Ministero dell'Ambiente e della Sicurezza Energetica. Pixel size 1 × 1 m.
1999	17.36	n.a.	-31.4	n. a.	Maragno *et al.*, 2009	Colour aerial photographs. Pixel size 1 × 1 m.
2003	16.68	0.23 (6)	-34.0	-33.1	this work	Orthophotos via WMS at Geoportale Regione Lombardia. Pixel size 0.50 × 0.50 m.
2006	16.38	0.23 (6)	-35.2	-34.3	Salvatore *et al.*, 2015	Orthophotos via WMS at Geoportale Nazionale - Ministero dell'Ambiente e della Sicurezza Energetica. Pixel size 1 × 1 m.
2011	15.85	0.20 (6)	-37.3	-36.5	this work	Ortophotos via WMS at Geoportale Nazionale - Ministero dell'Ambiente e della Sicurezza Energetica. Pixel size 1 × 1 m.
2015	15.54	0.22 (6)	-38.6	-37.7	this work	Orthophotos via WMS at Geoportale Regione Lombardia (pixel size 0.50 × 0.50 m) and at Provincia Autonoma di Trento (0.20 × 0.20 m).
2020	13.30	0.84 (9)	-47.4	-44.1	this work	Sentinel-2 satellite image taken on 18 Sept 2020 available at Copernicus Data Space Ecosystem | Europe's eyes on Earth. Pixel size 10 × 10 m.
2022	13.11	0.75 (6)	-48.1	-45.2	this work	Sentinel-2 satellite image taken on 13 Sept 2022 available at Copernicus Data Space Ecosystem | Europe's eyes on Earth. Pixel size 10 × 10 m.
2023	12.87	0.67 (6)	-49.1	-46.5	this work	Sentinel-2 satellite image taken on 8 Sept 2023 available at Copernicus Data Space Ecosystem | Europe's eyes on Earth. Pixel size 10 × 10 m.

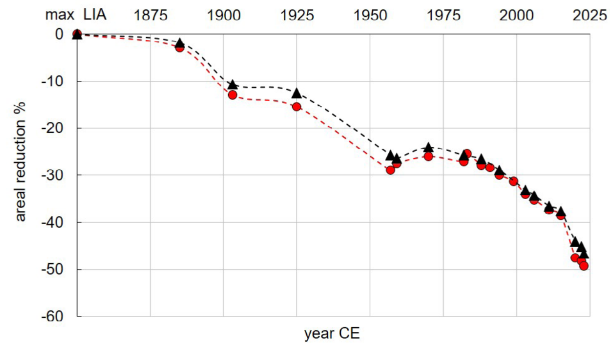

Figure 4a - Adamello Glacier areal reduction (%) from the LIA (ca. 1850) to 2023. Red circles refer to variation of the main glacier body (%); black triangles indicate areal variation (%) considering also the fractioned smaller glaciers detached from the main body since the LIA (see table 1 for details on areal extension and the number of fractioned glacial bodies).

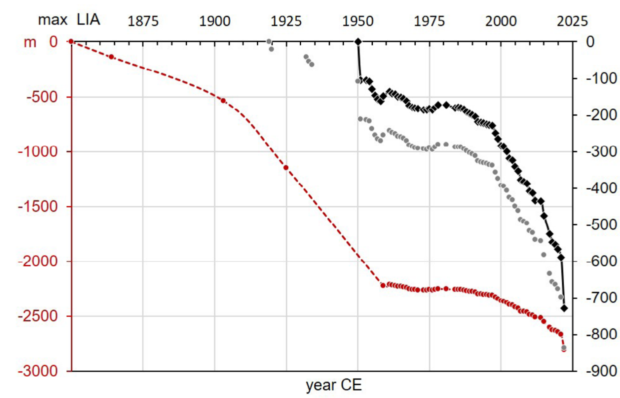

Figure 4b - Time - distance curves of northern tongue of Adamello Glacier (Mandrone Glacier Auct.). In red, the t-d curve reconstructed from the LIA, using terrain data (for frontal margin position during the LIA), historical maps and glaciological campaign data; in gray, t-d curve reconstructed using glaciological campaign data; in black, an enlargement of t-d curve from 1950 to present, considering glaciological campaign data validated from map and aerophotographic documents.

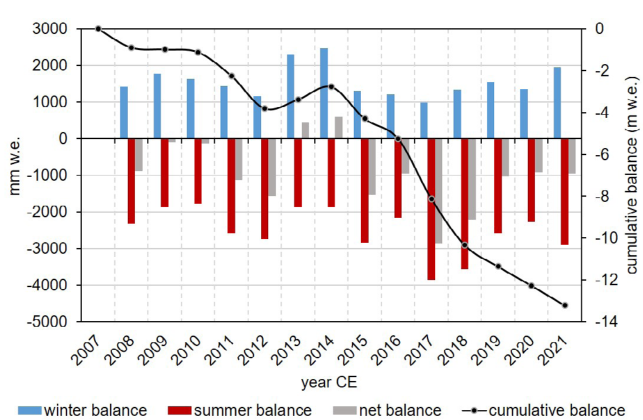

Figure 5 - Winter, summer and net balances of Adamello Glacier, since the hydrological year 2007-08. In bold, the cumulative mass balance, which shows a total loss of 16.8 m w.e. (data available at Meteotrentino and in Baroni *et al.* (Eds), 2018, 2019, 2020a, 2020b, 2022, 2023). Location of ablatometric stacks is in fig. 2.

ICE CORE DRILLINGS ACTIVITIES AT THE ADAMELLO GLACIER

The interest for drilling the Adamello Glacier comes from two factors: (1) its thickness, which could correspond to a long-time interval, and (2) the temperate conditions. Obtaining climatic information from temperate glaciers is a challenge that the ice core community is facing to exploit warming glaciers as paleoclimatic archives. Currently, there is no available information about ice temperature at Pian di Neve, but the conditions of the glaciers at that site are surely temperate. This is supported by the features of the ice cores extracted there during the last years. They present large portions of compact ice where bubbles are completely absent. This is regelation ice, formed by the freezing of water-soaked firn during autumn and early spring. Additionally, during drilling activities, the water filling the opened borehole remained constantly liquid, and forms related to melting processes (water pipes, lenses, changes in bubble distribution, veins filled with liquid water) were constantly found. These indications confirm that the temperature of the ice is close to the pressure melting point along the entire ice column.

The first drilling activities on the Adamello Glacier were carried out to retrieve samples for environmental and biological studies. The Adamello Glacier was chosen because of its extent and, most of all, for its thickness that was known to exceed 240 m in the upper sector (Frassoni *et al.*, 2001; Picotti *et al.*, 2017) and relatively low elevation. In fact, at low elevation sites the convective transport of material from the surrounding valleys is enhanced, increasing the possibility to have biological material deposited on the surface (Frassoni *et al.*, 2001; Nakazawa *et al.*, 2005; Pelfini and Gobbi, 2005). In 2015, a shallow firn core reaching the depth of 5.73 m was drilled in Pian di Neve. The idea was to extract organic material and environmental-DNA from snow and firn samples. This work was done in the framework of the POLLICE (Pollen in Ice) Project, funded by the Edmund Mach Foundation and Provincia Autonoma di Trento. The following parameters were investigated: physical properties of firn, stable isotope ratio, plant biodiversity (assessed through eDNA metabarcoding and conventional light microscopy analysis of pollen). The inspection and interpretation of the data allowed to identify a stratigraphic signal encompassing two years and highlighted pollen and plant remains within the distinct layers of snow and firn. Thanks to DNA metabarcoding, it was possible to describe several plant species, representing the broad taxonomic biodiversity of the catchment area (Vernesi *et al.*, 2017; Varotto *et al.*, 2021). This initial achievement paved the way for further research, demonstrating that valuable climatic and environmental records can be retrieved even from low elevation and temperate Alpine glaciers. Given these premises, in 2016, a 46 m ice core (ADA16) was drilled at the Pian di

Neve (10.52° E, 46.15° N; fig. 1). The drilling was performed using an electro-mechanical system that provides ice cores with a diameter of 80 mm. Core cutting residues (chips) were also recovered for each drilling run, with a spatial resolution corresponding to the length of single ice sections (from 50 to 80 cm). The drilling operations were done in collaboration with Provincia Autonoma di Trento, Edmund Mach Foundation (FEM), MUSE Science Museum of Trento, University of Milano Bicocca and ENEA Casaccia. Research activity on ADA16 was done within the CALICE research project, financed by the Euregio Science Fund, involving the Edmund Mach Foundation, the University of Innsbruck (UniInnsbruck) and the Free University of Bolzano (UniBZ). The major objective of the activity was to test the preservation of seasonal stratigraphic signals, in preparation for a drilling expected to reach the bedrock, which at the Pian di Neve was estimated to lie at ca 270 m below the snow surface (Picotti *et al.*, 2017). Apart from the observation of eventual seasonal oscillations, which were identified for black carbon and pollen, another aim of the project was to evaluate the changes in plant biodiversity through the study of pollen and DNA present in the glacier ice and compare them with the plant biodiversity data collected for the surrounding area (Festi *et al.*, 2021). Focusing on insoluble compounds present in the ice (black carbon, pollen, radionuclides attached to mineral particles), it was possible to accurately date the ice core. The major peak in ^{137}Cs activity (at a depth of 32.0 ± 0.3 m below the surface) was attributed to the maximum intensity of fallout from atmospheric nuclear bomb testing which occurred in 1963 while a second peak in ^{137}Cs at 9.5 m depth, was hypothesised to reflect the signal of the 1986 Tchernobyl accident (Di Stefano *et al.*, 2019, 2024). In temperate ice, compounds associated with insoluble particulate matter, such as radionuclides (Livens and Baxter, 1988), are indeed less subject to relocation and signal destruction than soluble ones (Eichler *et al.*, 2001; Avak *et al.*, 2018). Combining information about the seasonality of pollen assemblages, black carbon and fallout radionuclides, the top of the core was dated to 1993 CE, while the bottom, at the depth of 46 m, to 1944 CE (Festi *et al.*, 2021). Such data confirm that even the upper sectors of the Adamello Glacier are subject to a negative mass balance, leading to the loss of the most recent climatic information.

After the ADA16 success, in April 2021 a new ice core (ADA270, fig. 1) was drilled at the Pian di Neve (3100 m a.s.l.; 46° 08′ 56.101″ N, 10° 31′ 30.995″ E) and reached the depth of 224 m below the surface. The drilling activity and the subsequent research activities fall within the ClimADA Project. This was funded by Cariplo Foundation of Lombardy Region and chaired by the Lombardy Environmental Foundation (FLA). The following institutions are participating: the Mountain Community of Val Camonica, the University of Milano Bicocca, the Paul Scherrer Institut (CH), plus other Universities in Lombardy and some private companies. The core of the project is the reconstruction of the climatic and environmental history of the Adamello Massif area, focussing on four time slices of the ADA270 ice core: i) the human impact of the last century, to evaluate the variability of the land use on this Alpine area; ii) the World War I period, when the Adamello area was involved in fierce battles between Italy and the Austro-Hungarian Empire; iii) the last two centuries of the LIA that strongly impacted the Alpine communities (both natural and human) and, iv) the bottom, and most ancient, part of the ice core, to define the depth-age relationship of the entire ice core.

The drilling activity produced 330 ice core sections, each ca 70 cm in length and with a diameter of 8 cm. An electro-mechanical system was used to drill the first 20 m, and a thermal system down to 224 m depth. The change in the drilling system was due to the temperate ice conditions of glacier ice. Below the upper 3.70 m of fresh seasonal snow that covered the glacier at the drilling date, only the first meters of glacier ice were well below the melting point owing to the penetration of the winter cold wave. Below a few meters, the temperature of the ice was close to the melting point and plenty of liquid water was found in association with the ice. As such, the electro-mechanical drilling system would have mixed cutting residues and liquid water, blocking the instrument into the hole. For these reasons, a new thermal core barrel was specifically developed for this campaign, according to a previous design (Schwikowski *et al.*, 2014). All the ice cores were sealed in plastic bags and put in insulated boxes. Once the drilling was terminated, they were transferred, maintaining the cold chain, to the EuroCold Lab at University of Milano Bicocca, where they are kept refrigerated, at a temperature of -30°C.

ADA270 ICE CORE

Preliminary data

The ADA270 ice core was drilled 222 m NE of the 2016 coring site. The bedrock underneath the central part of the Pian di Neve plateau presents a concave shape that is interpreted as a glacial cirque, with a maximum ice thickness of 268 ± 5 m (Picotti *et al.*, 2017). Previous geophysical measurements provided similar results and estimated the glacial cirque bottom to lie at an altitude of 2860 m a.s.l. (Bonardi *et al.*, 1995, Carabelli, 1962). Toward NE, in the direction of the Madrone tongue, this buried cirque presents a threshold that rises about 100 m above the circus floor (Frassoni *et al.*, 2001). The ADA270 ice core was not drilled in the deepest point but closer to the glacial cirque saddle. When the drilling reached a depth of ca. 222 m, some rock fragments (size ca. 0.5 cm) were observed. From a preliminary analysis, they resemble the tonalite forming the bedrock of the Adamello Massif. Bottom shear could explain the inclusion of basal rock fragments in glacial ice.

There are not many publications dealing with the thickness of the shear zone at the bottom of glaciers, but estimates indicate that it typically corresponds to ca. 20% of total thickness for cold and polythermal high-elevation glaciers (e.g., Jenk *et al.*, 2009; Gabrielli *et al.*, 2016; Uglietti *et al.*, 2016; Licciulli *et al.*, 2020). For temperate glaciers, the shar zone is reduced to 10-15 % of the total thickness, because the presence of meltwater lowers the friction (e.g., Kaspari *et al.*, 2020). Assuming that the small clasts indicate the top of the basal shear zone, we can estimate the total thickness of the ice at the ADA270 drilling site to be 253 (±10) m, corresponding to 227.7 (±9) m w.e. if we assume a constant ice density of 0.9 g cm^{-3} (i.e. the density of solid ice).

As demonstrated by the dating of the ADA16 ice core, the surface of the glacier in 2016 was dated to year 1998 (±3) when using ^{210}Pb, and to 1993 (+0/-3) by means of annual layer counting (pollen and black carbons; Festi *et al.*, 2021). At the same time, the Tchernobyl ^{137}Cs peak was measured at 6.6 m w.e. (9.5 m real depth) while the ^{137}Cs feature related to the 1963 peak in nuclear tests was found at 27.1 m w.e. depth (32 m real depth; Di Stefano *et al.*, 2024). The two peaks represent the 1986 and 1963 annual layers, respectively. By means of annual counting and the ^{137}Cs reference horizons, the best estimation of the mean annual accumulation rate (MAAR) from 1963 to 1986 is 0.90 ± 0.03 m w.e. a^{-1} (Festi *et al.*, 2021). Using this MAAR for the topmost 10 m of ADA16, the vertical distance between the Tchernobyl reference horizon and the surface of the glacier in 2016 spanned only 7.3 years, thus dating the surface to 1993. In terms of stratigraphy, the lack of the last 20 years makes the application of the ^{210}Pb dating method less precise (Festi *et al.*, 2021).

As confirmed by ADA16, the Pian di Neve area is recording a negative mass balance, meaning that year after year the glacier is losing its surface layers. According to this, the age of the outcropping ice is becoming progressively older. Mass balance analysis indicates that, from 2016 to 2020, the Pian di Neve lost around 5.52 m (±0.15) of water equivalent (fig. 2; Meteotrentino *et al.*, 2022; Baroni *et al.*, 2018, 2019, 2020a, 2020b, 2022, 2023). The ADA270 measurements are still in progress, and, for this reason, we will now consider data inferred from the ADA16 core. Using the ADA16 MAAR, a loss of 5.52 m w.e. corresponds to a loss of 5.5 years in terms of ice stratigraphy. This would imply that the surface age at the end of 2020 corresponded to the year 1988 (±1 year), only 1.1 m w.e. above the Tchernobyl reference horizon. At the same time, if the accumulation rates between ADA16 and ADA270 sites are similar, we can estimate the 1963 ^{137}Cs peak to be at 22.2 m real depth in the ADA270 core. In fact, the density record for ADA270 is currently unavailable. Therefore, discussions about stratigraphy and of the stratigraphy uses the real depth; in contrast, the age-depth model is calculated in water equivalent, based on the average annual accumulation used as input for the model (in w.e.).

Composition of the ice and signal preservation

To preliminarily explore whether environmental signals are preserved in the ADA270 ice core, initial data are presented in fig. 6, where the concentration of major ions in the fresh snow that was covering the glacier during the drilling operation is compared to the concentration found in the top-most 1.6 meters of glacier ice. We assume that the ionic content of fresh snow is a benchmark for the perfect preservation of glacio-chemical signals derived from the atmosphere. This is because the analysed snow was not affected by melting, nor prior to the drilling campaign, neither during it.

Median concentration of fresh snow (22 samples, 1.47 m w.e.) is significantly higher than the concentration observed in glacier ice (21 samples, 1.64 m w.e.) for all the considered ions, with the exception of $NH4^+$. The significance was assessed applying the non-parametric Kruskal-Wallis test (95 % significance). This agrees with what is known from previous studies: soluble impurities, and in particular ionic ones, are promptly removed from firn, the upper porous part of a glacier, when liquid water is present, even temporarily (Eichler *et al.*, 2001). As the Adamello Glacier at the ADA270 drilling site has experienced a negative mass balance for many years, disturbances related to the effects of meltwater were expected.

The only ion not affected by melting seems to be ammonium, whose median value in fresh snow is comparable (statistically not different) to glacier ice (17.7 vs 12.5 µg g^{-1}). This also agrees with previous results showing that ammonium is among the less affected ions by meltwater-induced mobilization (Eichler *et al.*, 2001; Moser *et al.*, 2024). Chloride as well is subject to limited depletion in ice. Despite its median concentration in snow is significantly higher than in glacier ice (41.6 vs 16.9 µg g-1), the associated Kruskal-Wallis p-value is 0.003, close to the critical value indicating no difference (0.005). Previous studies, as for ammonium, showed that chloride as well is only partially impacted by meltwater in glacier ice (Eichler *et al.*, 2001). The hypothesis is that both ions, thanks to their chemical features, are incorporated into the ice molecular lattice during metamorphosis from snow to ice, making them less prone to removal by meltwater compared to ions present at the ice grain boundaries (Wolff, 1996).

According to these results, processes occurring in temperate ice are surely affecting the preservation of chemical signals in the ADA270 ice core, but some signals seem better preserved than others, potentially allowing for a partial retrieval of paleoclimatic signals. Nevertheless, further investigations are needed to better constrain the paleoclimate potential of temperate ice, but in accordance with what was also observed in the ADA16 ice core (Festi *et al.*, 2021), premises are encouraging.

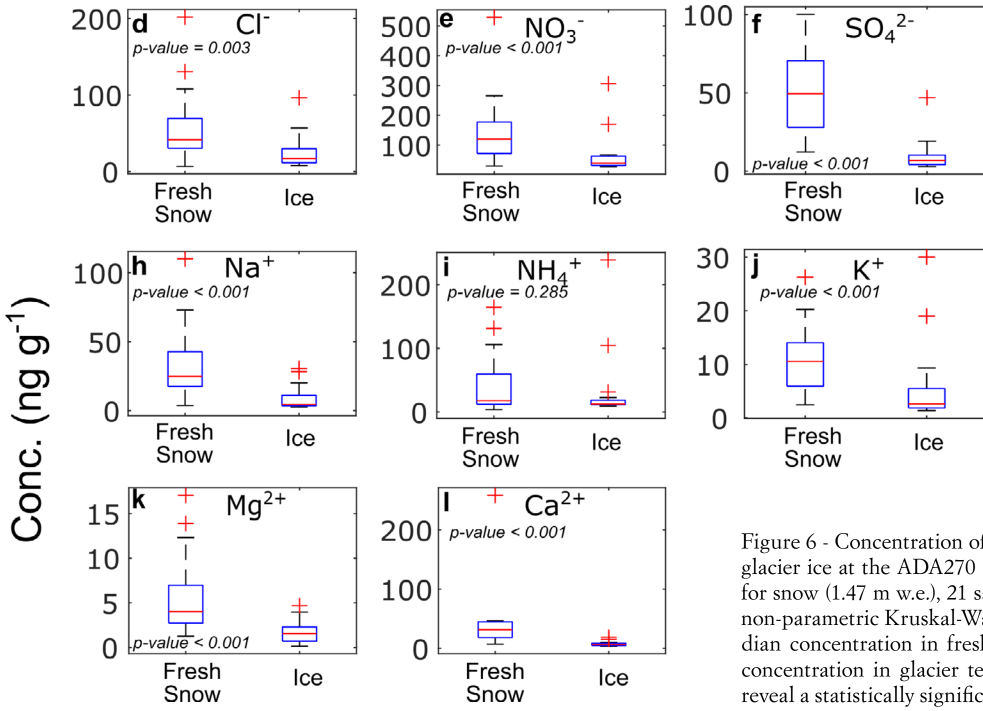

Figure 6 - Concentration of major ions in fresh winter snow and in glacier ice at the ADA270 drilling site. 22 samples are considered for snow (1.47 m w.e.), 21 samples for glacier ice (1.64 m w.e.). The non-parametric Kruskal-Wallis test was applied to assess if the median concentration in fresh snow was different from the median concentration in glacier temperate ice. P-values minor than 0.05 reveal a statistically significant difference.

Age model

By using the one-dimensional Dansgaard-Johnsen ice-flow model (Dansgaard and Johnsen, 1969), the age-depth relationship at the ADA270 drilling site was estimated, despite the exact total ice thickness at this point is not known with precision (fig. 4). For the depth–age relation, are considered constant accumulation and steady-state flow, modify for the temperate glaciers (Neff *et al.*, 2012) using the total ice thickness, estimate to be 227.7 (±9) m w.e., the surface accumulation rate of 0.9 m w.e. a^{-1}, and the basal velocity/surface velocity ratio of < 0,1 (Waddington *et al.*, 2001).

From the mass balance measurements spread across Pian di Neve, the mean annual accumulation rate is similar for this entire sector of the glacier, with a value of 0.90 ± 0.03 m w.e. a^{-1}, as estimated by Festi *et al.* (2021). Such values are similar to accumulation rates measured at nearby glaciers, like the Ortles, with 0.85 m w.e. a^{-1} (Gabrielli *et al.*, 2016) and the Silvretta Glacier, with 0.9 m w.e. a^{-1} (Pavlova *et al.*, 2015). All these values refer to similar periods: 1963-2011 for the Ortles ice core (Gabrielli *et al.*, 2016); 1940-2010 for the Silvretta ice core (Pavlova *et al.*, 2015).

Modelling results are shown in fig. 7. Since constraining age markers are currently missing below the Tchernobyl reference, ice ages below this point present an indicative uncertainty of at least 15 %. This uncertain is reasonable for a temperate glacier (e.g., Kaspari *et al.*, 2020). In any case, due to the lack of constraining information from dated age horizons for the bottom part, a relatively large uncertainty of approximately 10% was assigned.

At Pian di Neve, owing to the negative mass balance, the glacier column entirely consists of glacial ice. This is because firn is completely missing owing to the negative mass balance of the last years and snow is only seasonally present. According to this, real depth can be easily approximated to ice depth using the density of solid glacier ice (0.9 g cm^{-3}). This assumption helps the interpretation of the age-depth model because the rheological properties can be assumed to be similar along the entire ice column. On these premises, the age-depth relationship is calculated down to 201.6 m w.e., corresponding to 224 m in terms of real depth. According to this model, still poorly constrained, the age of the ice at 201.6 m w.e. would be approximately 2000 years, corresponding to -12 CE (or 2000 years before 1988), with an estimated uncertainty of 300 years. Using this age-depth relationship, the ice formed during the Great War (WWI, 1914-1918) should be at a depth between 49.5 and 54 m w.e. (55 to 60 m depth). Ice from LIA (around 1400 to 1850) would span the interval between 67.5 and 144 m w.e. (75 to 160 m depth), while the Medieval Climatic Anomaly, i.e., from 800 to 1300 (Mangini *et al.*, 2005; Mann *et al.*, 2009; Wanner *et al.*, 2022), would correspond to the depth interval between 157.5 and 180 m w.e. (175 to 200 m depth).

Certainly, results from the age-depth model described here must be handled with extreme caution and considered only indicative. The only constrains available regard the upper part of the core while information about the ice flow in the deepest part of the glacier is missing. Moreover, no age-depth relationship was developed for glaciers under temperate conditions. However, a basal age of about 2000 years is not unrealistic. Staying in the Alpine milieu, ice core drilled at Colle-Gnifetti (Monte Rosa) have a basal age that can reach 9000 years BP at a depth of 62 m w.e. (Jenk *et al.*, 2009) with indication for late Pleistocene ice present at the very bottom. The ice core extracted from the summit ice cap present at Mt. Ortles (Gabrielli *et al.*, 2016), revealed an ice age of ca 100 years at a depth of 45 m w.e. but it quickly increased to ca 7000 years at a depth of ca 61 m w.e. Of course, these glaciers are cold, at least in their deep portions, while the Adamello Glacier is entirely temperate. Such difference could imply a significant deviation of the age-depth relationships, also considering the peculiar bedrock topography, which is quite protective at the drilling site due to the submerged cirque. To shed light on this point, additional data are mandatory. Radiocarbon dates, together with the analysis of signal seasonality and hopefully with the identification of specific temporal markers (outstanding dust events) will hopefully improve the dating of the ADA270 ice core.

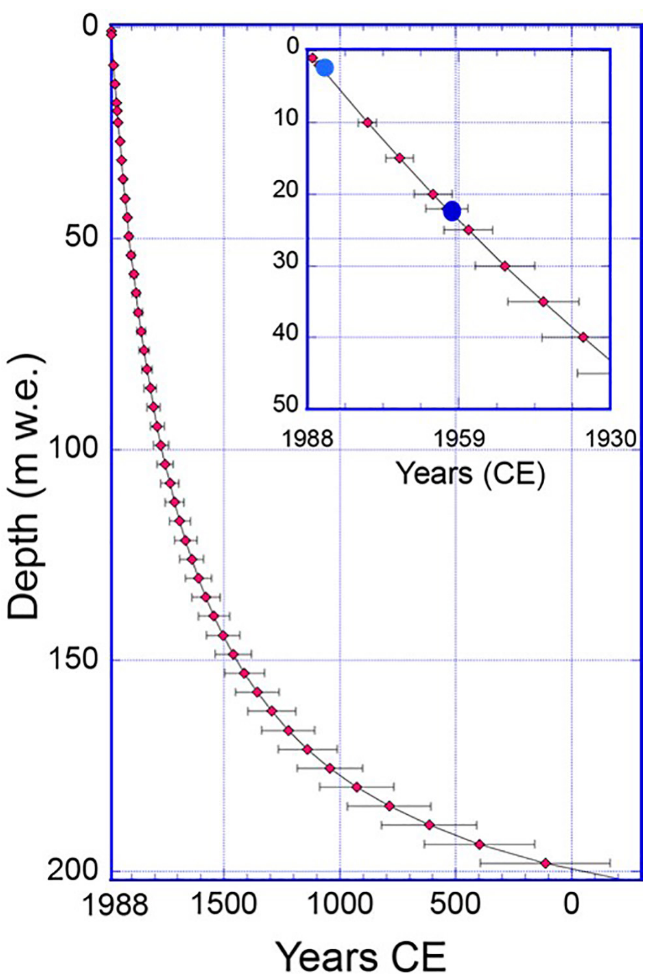

Figure 7 - Depth vs age one dimensional model till 201.6 m w.e. (224 m ice) depth with error bars. The blue dots in the graph detail represent the extrapolation of the Tchernobyl (1986) and 1963 thermonuclear test horizons extrapolating from ADA16 (see text).

Visible layers stratigraphy

Throughout the whole ADA270 ice core, a total of 127 layers presenting visible impurities were observed (fig. 8). The layers are between 0.1 and 16 cm thick and can be divided into two main types. Greyish/blackish layers are the most frequent and, apart from mineral dust, they include palynomorphs, microcharcoals, diatoms and organic matter. Their origin is probably due to spring/summer convective winds capable of carrying impurities on the glacier from the downward valleys and villages. Few layers could also be related to the accumulation of cryoconite at the exposed surface of the glacier, which only forms when bare ice is melting (Takeuchi *et al.*, 2001). The presence of charcoal could be mainly linked to fires that burned the forests blanketing the slopes of the valleys below the glacier and to human activities. On the other hand, brownish/orangish layers, which are intercalated to the darker ones, result from long distance transport of mineral dust from the Saharan region; these layers are a common feature of alpine glaciers (Maggi *et al.*, 2006).

Looking at the overall sequence, the decrease in frequency and thickness of these events over depth is evident. Above 41 m depth, 70 layers containing impurities were observed, with a frequency of 1.7 layer m^{-1}, while below that value, the frequency decreases to 0.3 layer m^{-1}. The interval between 62 and 69 m depth shows a local increase in frequency, with 1.3 layer m^{-1}.

Impurity layers are well preserved above the depth of 41 m and could be used to develop a chronology; below this threshold, the frequency of the layers is almost six times lower. The difference does not reflect a change in climate conditions but is due to the thinning of the impurity layers resulting from the compression of the ice above. Below the depth of 41 m, therefore, only layers particularly thick or dark in colour can be seen with the naked eye. The increase in frequency between 62-69 m depth cannot so far be explained and in-depth analyses are required to better understand this signal. Between 65 and 125 m depth, the visible layers present various degrees of tilting. The inclination reaches a maximum of about 50° at around 80 m depth. The tilting then gradually decreases and is again almost horizontal from a depth of 110 m to the bottom of the core. The tilting of the visible layers constitutes another source of uncertainty for the chronological constrain and the interpretation of ADA270. The change in inclination identifies a portion of the glacier that likely has undergone, or is still undergoing, a different dynamic behaviour, which involves the deformation of the original stratigraphy. There are no clear traces of folds in the visible layers, and even the transitions between different ice facies (with bubbles or without bubbles) do not show folding structures. A clear explanation for this tilted part of the glacial ice is still missing but we can make some hypotheses. Despite the Pian di Neve being a large plateau, it is fed by at least two main glacial flows: one coming from the western slope, between Corno Grande and Monte Adamello, and the second from the eastern slope, i.e., from Monte Fumo. It is also worth noting that the southern part of the Pian di Neve feeds small effluences facing south (Adamè, Salarno, Corno Salarno, and Miller Superiore glaciers; fig. 1). Such a configuration is quite complex and could have been affected by major changes in terms of relative flow contributions. A variation of the ice flow direction at the drilling site cannot, therefore, be excluded. It is also necessary to consider that the deepest part of the Pian di Neve is located within a glacial cirque protected by a notable threshold. This morphological element forces the ice of the deepest part to rise from the bottom of the cirque, for about 80-100 m (Carabelli, 1962; Frassoni *et al.*, 2001; Picotti *et al.*, 2017). Analyses on the ice facies and impurity content may help clarifying the meaning of the tilting of the dust layers and the implications in terms of chronology.

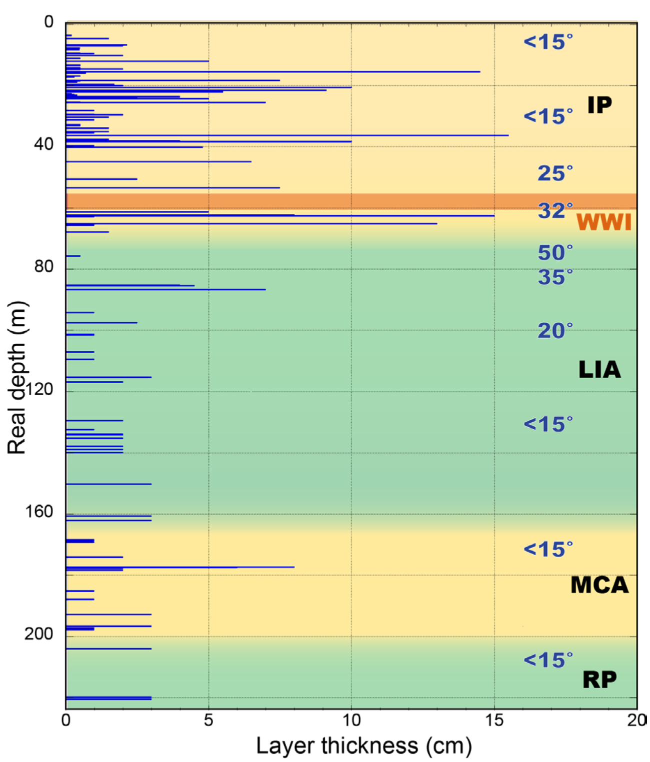

Figure 8 - Visual stratigraphy of ADA270 with dust layers thickness, tilting of the layers (only indicated in numerical form) and estimated age intervals. Layers with angle < 15° are considered sub-horizontal. The depth of the various chronological intervals was calculated with the Dansgaard-Johnsen age model described in text. The orange bar represent the depth estimation of the World War I layers. (IP = Industrial Period; WWI = World War I; LIA = Little Ice Age; MCA = Medieval Climate Anomaly; RP = Roman Period).

CONCLUSION

The Adamello Glacier is the largest and thickest temperate glacier in Italy. Mass balance, areal extension, front position and energy-mass balance all confirm that the glacier is recording a strong retreat, both in terms of area and thickness. In 2016, the ice exposed at the surface of the glacier at Pian di Neve was dated around 1990, implying the loss of ice corresponding to the years between 1990 and 2016 (Festi *et al.*, 2021). The analysis of the glacier mass balance provides a similar picture, with a loss of 16.8 m of water equivalent from 2008 to 2022, i.e., 1.2 m w.e. yr^{-1}. Since the LIA glacial advance, the Adamello Glacier lost more than 49% of its surface (considering the main body) recording the withdrawal of the northern tongue of more than 2800 m. But despite the rapid decline and the severe melting which affects the glacier even in its upper sectors, the two ice cores drilled in 2016 and 2022 at Pian di Neve show that environmental signals are at least partially preserved in the Adamello Glacier temperate ice, opening the possibility to obtain useful records from melting temperate glaciers. This is confirmed by preliminary data about the concentrations of ions, black carbon, pollen, radionuclides and by the occurrence of well-preserved visible layers rich in impurities across the entire ADA270 core. The preliminary dating of this ice core indicates an estimated age of ca 2000 years at the core bottom. If this is correct, the paleoclimatic investigation of the Adamello Glacier will shed light on the climate of the late Holocene, including key intervals such as the Medieval Warm Period and the LIA. According to such preliminary results, ice cores drilled at temperate glaciers impacted by the effects of climate change can still provide useful climatic and environmental records, limiting, at least partially and temporarily, the detrimental effects of climate change on ice core science. Until now, temperate glaciers were only sporadically considered for ice core drilling and the few available ice cores allowed to gather environmental information about the last decades. Preliminary data here presented indicate that ADA270 is likely to allow it to go much further back in time, disclosing the importance of temperate glaciers for paleoclimatic reconstructions.

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AUTHORS CONTRIBUTE

VM, MCS and CB conceived the idea for this work; VM, MS, TJ drilled the ADA16 and ADA270 ice cores. VM build-up the ADA270 depth-age model; GB, SB, AE processed ice samples and performed chemical analyses; GB, with the help of AE and MS, interpreted chemical data; MCS, CB and AC provided the reconstruction of the Adamello Glacier surface maximum extension during the LIA; MCS and CB reconstructed the glacier evolution from the LIA to present day and the time-distance curve; CC and VM provided data for the Pian di Neve mass balance and reconstructed the lowering of the glacier surface; CM and VM provided the reconstruction of the visual stratigraphy of ADA270 and the interpretation of dust layers record; All the authors contributed actively to write the manuscript.

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