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NOW OR NEVER:
THE STUDY OF DISAPPEARING ICE ARCHIVES IN THE TIME OF GLOBAL WARMING

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ABSTRACT: Mountain glaciers in the Alps can provide detailed information on past climatic conditions. Regrettably, their persistence is currently threatened by the ongoing warming. This situation generates public concern and the need to recover and preserve ice cores before their stratigraphy is permanently compromised. This contribution reports on recent ice core drillings in the Eastern Alps implementing new approaches to directly link the climatic signal retained in the ice with the palaeo-environmental component of the ice.

KEYWORDS: Pollen, environmental DNA, mountain glacier, cryopalynology, ice cave, timescale

1. INTRODUCTION

Since the first signs of global warming have been recognised, the scientific community committed to provide evidence of past and current climate change, as well as an understanding of its causes, to support policymakers and governments in their decisions. In the frame of these investigations, it has been recognised that the warming is particularly severe in the European Alps, where temperature is rising at twice the global rate (IPCC 2013).

The rapid retreat of alpine glaciers is probably the most striking evidence of the drastic effects of the ongoing climate warming. Recent estimations speculate that European glaciers experienced a loss in ice volume of 49% in the period 1900-2011 (Huss, 2012). Their retreat has a considerable impact on both the scientific community and the public, as it can be witnessed on a timescale as small as a lifetime (Diolaiuti et al., 2012). This situation clearly generates public and scientific concern, creating an urgent need for detailed investigation of glacier content, before the ice bodies become permanently compromised. It is, indeed, a "now or never" situation, as the increased summer ablation, leading to progressive percolation, is already compromising the integrity of glaciers as palaeo-archives. Furthermore, while the vanishing of the surface cryosphere is evident, the decline of the underground cryosphere is less striking, yet equally concerning. Ice masses hosted in caves have a great potential for palaeo-environmental studies (e.g. Luetscher et al., 2005), providing complementary information to mountain glaciers, as they occur at lower altitudes and generally, where surface glaciation is altogether missing (Kern & Perşoiu 2013).

In the past decades, main efforts of ice cores studies in the Alps converged on the western part of the mountain range (i.e. Monte Bianco and Monte Rosa Massifs, ICB, http://geomatic.disat.unimib.it), because of their higher elevation, which let presume the possibility of retrieving intact ice records. In the Eastern Alps little research has been done (i.e. Vernagtferner, von Gunten et al., 1982). Finally, the approach used to study glacier ice cores considerably resembled that developed for polar ice caps, which was established to obtain quantitative palaeo-climatic reconstructions. This practice has given little attention to the biological proxies present in the ice, e.g. pollen (Vareschi, 1934; Bortenschlager 1970) and left highly unexplored the possibility of directly linking climatic and environmental evidence enclosed in glaciers. This gap has finally been recognised by both ice core scientists and palaeo-ecologists, who began developing new approaches, to exploit glacier ice in a more comprehensive way, including well established palaeo-environmental proxies, e.g. pollen, as well as new generation proxies, e.g. environmental DNA (eDNA). The present contribution, based on published data and personal engagement in ongoing research projects, reports on: i) filling the gaps in ice core studies in the Eastern Italian Alps; ii) recent advances in pollen as a chronological tool for ice core; iii) the potential of mountain glaciers as palaeo-environmental archives.

2. METHODS

2.1. Filling the gaps in the Eastern Alps

Choosing the ideal site is the key of success of every palaeo-climatic and palaeo-ecological study. In a period of climate warming this proves to be a challenging task, especially for ice core drilling in the Eastern Alps, where glaciers are found at lower elevation. Here two drilling sites are presented.

The Alto dell'Ortles Glacier is the highest glacier in the Eastern Alps, with an altitude ranging from 3018-3905 m a.s.l. The ice body is located close to the border between Italy, Austria and Switzerland (Figure 1), on the north-western slope of the Mt. Ortles, and covers an area of about 1.04 km^2 (Gabrielli et al., 2012). The features making Alto dell'Ortles a suitable site for ice core studies in the Eastern Alps are: i) its high altitude setting; ii) the great thickness of the ice, ca. 75 m; iii) the presence of cold ice (Gabrielli et al., 2012); iv) an excellent lamination of the exposed ice layers down to bedrock observed prior to drilling (Gabrielli and others, 2010). Finally, the glacier is also a good candidate for successful cryopaly-

nological analyses, due to the vicinity of the vegetation and the efficient uplift by thermic winds that ensures an effective transport of pollen from the surrounding area. Project Ortles aims at studying the glacier as an indicator of past and current climate change, and includes the study of pollen, isotopes, major ions, trace elements and levoglucosan as determined in ice cores, as well as the investigation of the glacier physical features and the surrounding permafrost areas. The goal of palynological analysis is to provide a pollen-based timescale of the cores, as well as to explore the potential of pollen analyses in ice core for palaeovegetational and palaeoclimatic reconstructions.

The Pian di Neve Glacier covers an 8 km² large plateau located in the Adamello Massif at an altitude of 3100-3400 m a.s.l. (Figure 1). With its ~270 m of depth, it is the deepest Italian glacier and, together with the adjacent Mandrone Glacier, it is also the largest glacier of Italy (Picotti et al., 2017). Pian di Neve was chosen as a drilling site for its suitability to study the interactions between climate, biosphere and human activities because of: i) the expected high time resolution due to the mighty ice thickness; ii) the vicinity of vegetation, due to its low altitude, which ensures an input of biological proxies; iii) its vicinity to the high industrialised Po Plain, which provides a long record of anthropic activity.

2.2. Advances in pollen as a chronological tool

The classical interpretation of pollen diagrams to detect annual variation in the pollen spectra is not very handy when dealing with thousands of samples, as it is often the case in the analyses of deep ice cores. Thus, novel approaches were developed to condense the complex palynological information of the core, and to provide a precise timescale. Both methods, hereafter summarised, were developed and tested on a 10 m (459 cm w.e. water equivalent) shallow core retrieved on the Alto dell'Ortles Glacier.

The first approach developed by Festi et al. (2015) is based on the extraction of the seasonal signal by principal components analysis (PCA) of pollen assemblages obtained by high level taxonomical identification (details in Festi et al., 2015). This approach allows to extract seasonal components indicative of the original flowering seasons and easily visualise the succession of different seasons (spring, early and late summer) along the core (Figure 2 a).

The second method is based on a "space-for-time" (or "depth-to-day" substitution) by pollen content of ice samples (depth) and daily pollen monitoring samples (day) of a nearby aerobiological station. By coupling the pollen content of firn/ice samples with the most statistically similar pollen assemblage of the airborne samples, a link can be established between pollen deposition at a specific sample depth on the glacier and a specific day of the year (DOY) of the daily monitoring (details on the method in Festi et al., 2017).

2.3. Ice cores as palaeoenvironmental archives

The Pian di Neve ice core was specifically recovered to obtain environmental information from the ice. CALICE- Calibrating biodiversity in glacier ice- is in fact the first ice core project mainly targeting the biological
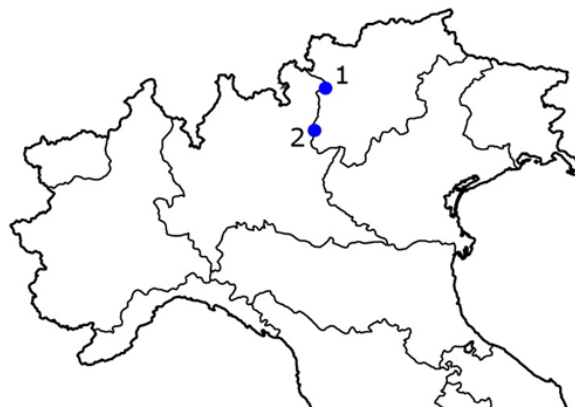

Fig. 1- Map of northern Italy showing the location of ice core drilling sites presented: [1] Alto dell'Ortles Glacier; [2] Pian di Neve Glacier, Adamello Massif.

component of the glacier. Pollen and plant eDNA analyses are conducted in order to reconstruct changes in biodiversity during the last 70 years, in relation with climate warming and human impact (changes in land use and practices, industrialisation, etc.). These results will be validated by biodiversity estimates from the region, obtained with remote sensing, historical archives and field surveys. This approach will generate the very first plant diversity record obtained by pollen and DNA analyses from an Alpine ice core, validated by historical biodiversity assessments. This approach significantly contributes towards the possible exploitation of mountain glaciers as palaeo-ecological archives.

However, every palaeo-ecological reconstruction should be established on a deep knowledge on how the proxies are incorporated and build up the signal object of analyses. Such processes are poorly investigated for pollen and DNA in glaciers. To fill this gap, direct and indirect approaches are possible: i) on site pollen/DNA monitoring; ii) combining pollen analyses from ice samples with mass balance modelling.

The first approach is currently implemented near the drilling site of Pian di Neve, where a daily pollen monitoring station has been set up. This data will provide important information on the variations in time of the pollen load transported by the air masses over the glacier, in terms of both quantity and pollen types. This pattern is presumably reflected by changes in pollen spectra and pollen concentration found in the ice.

The second and indirect approach was already tested on the Alto dell'Ortles shallow core (Festi et el., 2017) by combining palynological results with the results of mass balance modelling for the drilling site (EISModel, Carturan et al., 2012). The mass balance model simulates accumulation and melt processes at hourly time steps. For each snow layer deposited (i.e. the water equivalent that accumulates at the surface of the snowpack during an hourly time step), the model provides its time and date of formation, as well as the air temperature during its deposition (Figure 3). For details on EISModel refer to Carturan et al. (2012).
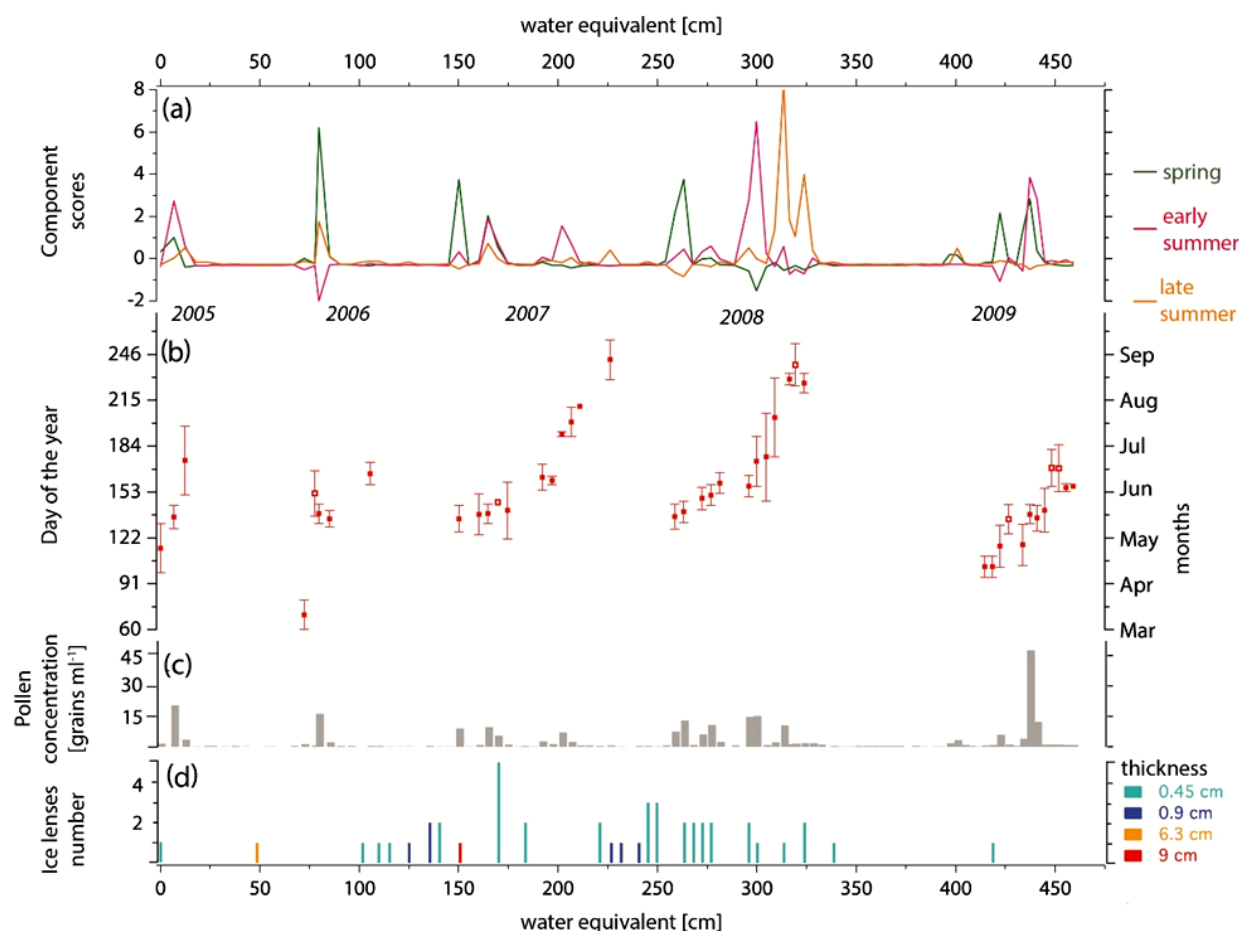
Fig. 2 - **(a)** Alto dell'Ortles firn core 2009 timescale (Festi et al., 2015) based on Principal Component Analyses. As every principal component (PC) condenses the seasonal information of the pollen spectrum, scores values should be interpreted as follows: a sample (w.e. depth down) presenting high component scores values for a specific PC is characterised by a pollen content reflecting predominantly the season corresponding to that particular PC. **(b)** Mean date (day of the year ± 1 sigma) obtained by using the depth-to-day method (Festi et al., 2017); empty squares represent inversions **(c)** Pollen concentration in the Alto dell'Ortles 2009 firn core. **(d)** Number and mean thickness (colour scale) of ice lenses per sample (Figure from Festi et al., 2017).

3. RESULTS

3.1. Filling the gaps in the Eastern Alps

Drilling expeditions on both the Alto dell'Ortles and Pian di Neve glaciers were successful despite the technical challenges associated with coring temperate glaciers, and a climatic and environmental signal was retained in the ice of both ice bodies.

In the frame of the Project Ortles two coring expeditions led by project leader Paolo Gabrielli (Ohio State University) were conducted. In 2009 a firn core of 10 m (459 cm w.e.) was retrieved, while in 2011 four deep cores of about 75 m (~60 m w.e.) were extracted. The dating of the deep ice cores based on 210Pb, tritium, beta activity and 14C analyses, provided a maximum age of the bottom layers of ~7 ka, during which it is presumed that the drilling site was continuously glaciated on frozen bedrock (Gabrielli et al., 2016). Pollen analyses have been performed on the short core at 10 cm resolution on 103 samples, and on one of the deep cores (C1) at 10 to 3 cm resolution, leading to ca. 1840 samples. Pollen concentration on the long core varied from 0 to 27 grains/ml and about 120 pollen and spore types were identified. The palynological data showed that an annual signal was retained in most of the core. The complete pollen-based timescale is currently being combined with the results of isotopes and dust analyses to accomplish a final multi proxy annual timescale.

Pian di Neve. In the frame of CALICE- Calibrating biodiversity in glacier ice - a 42 m core has been retrieved in April 2016 from the centre of the glacier by a drillers team lead by Valter Maggi (Milano Bicocca University). First results of pollen analyses on 200 ice samples show a pollen concentration from 0 to about 35 grains/ml.

3.2. Advances in pollen as a chronological tool

Both statistical methods were tested on the Alto dell'Ortles short core. The pollen content of firn samples (~30ml each) was very variable, and concentration values range from 0 to 47 grains/ml. Pollen grains were mostly characterised by an excellent state of preserva-

tion, and their identification led to a pollen spectrum of 64 pollen types (for details refer to Festi et al., 2015). The seasonal variations reconstructed with both methods are shown in Figure 2, together with changes in the concentration of pollen and spores. Both methods led to the conclusion that the core includes five years of snow accumulation (2005-2009) and highlight a substantial difference in the pollen distribution patterns in the snow, both within and among flowering seasons. Flowering seasons stood out distinctively as layers with high pollen concentration, variable inter-annual thickness and seasonality patterns. According to their thickness and vertical distribution of pollen, the flowering years clustered in two groups: 2005 and 2006 vs. 2007, 2008 and 2009. Specifically, the flowering seasons of 2007 and 2008 corresponded to very thick firn layers, into which pollen was distributed with a clear seasonal pattern. In contrast, the flowering seasons of 2005 and 2006 were characterised by a lower firn thickness, the occurrence of a thin lower layer with a distinct spring pollen content, and a thin upper layer containing mixed spring/summer pollen. On the contrary, the "winters" (October to February) were clearly visible as firn layers of different thickness, which are free (or nearly free) of pollen. Winter 2007/08 was the thinnest with only 33 cm w.e., followed by 2006/07, 2005/06, and finally 2008/09 with 91 cm w.e. this method allows very precise dating of the time of deposition of snow samples according to their pollen content.

Ortles *deep core*. Pollen concentration varied from zero to 27 grains/ml and about 120 pollen and spore types were identified. The data show that an annual signal was clearly retained in most the core. The annual timescale is currently under construction by combining the results of pollen, isotopes and dust analyses to refine the depth age model by Gabrielli et al. (2016).

Pian di *Neve*. First results of pollen analyses on 200 ice samples indicate that an annual signal is preserved in the deeper strata of the core.

3.3 Ice cores as palaeoenvironmental archives

Preliminary results of pollen analyses of the Pian di Neve core indicate a fairly rich palynological diversity, which combined with the ongoing eDNA analyses will provide a good record of past plant diversity. The pollen spectra were characterised by ca. 80 pollen and spore types, reflecting alpine, subalpine, montane and Mediterranean vegetation types. Pollen grains of crops (e.g. *Secale* cereale, *Zea mays*) as well as cultivated trees (*Castanea sativa*, *Juglans regia*, *Olea europaea*) and neophytes (*Ambrosia* sp., *Eucalyptus* sp.) also occurred in the analysed samples. Diatoms, fungi spores and butterfly scales were among the non-pollen- palynomorphs found in the samples. This supports the hypothesis that analyses of biological proxies on glaciers can generate useful palaeo-environmental record.

With respect to the advances in process understanding of the formation of the pollen signal in the ice, comparison between pollen-based timescale and mass
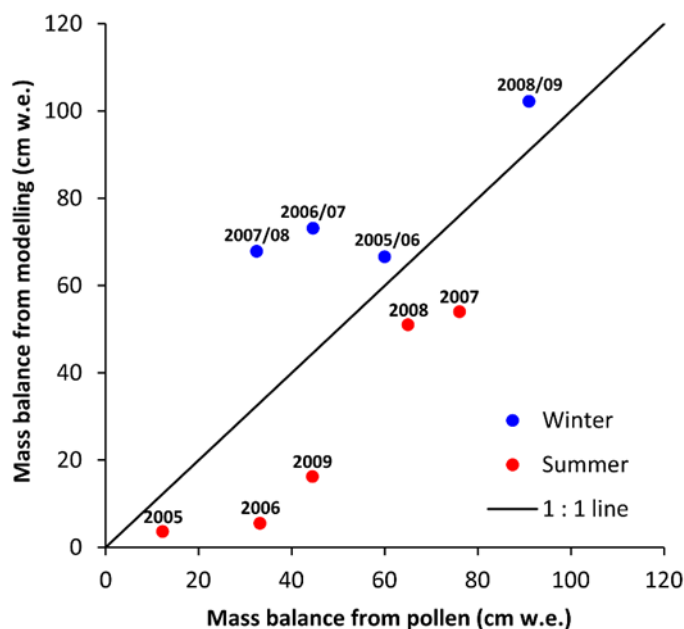

Fig. 3 - Comparison of the winter and summer mass balance as obtained by pollen dating and modelling (EISModel).

balance modelling revealed the great potential of pollen for inferring past climatic conditions at a sub-seasonal resolution in ice core records. Based on the pollen content in the Alto dell'Ortles strata of the shallow core (Figure 2), three main types of pollen assemblages could be identified and correlated with the corresponding climatic conditions inferred for by the model for that season: i) thin pollen-rich layers with fairly clear date order but overlapping of principal components (i.e. 2005 and 2006, Figure 2). According to the modelling, such layers were the result of intense summer ablation, thus pointing to warm and dry summer conditions; ii) thick layers with substantial pollen concentration and well-distinguished succession of dates (i.e. 2007 and 2008). For these layers the model showed a spring/summer snow deposition generated by copious precipitation and low temperatures, and characterised by negligible melting; iii) thick pollen free layers, reflecting autumn and winter snow deposition. Figure 3 shows the comparison of the mass balance reconstructed according to the pollen-based timescale with those by the mass balance model EISModel (Festi et al. 2017). Remarkably, these are the first results pointing to the potential of pollen to reconstruct not only past vegetation, but also climate conditions and snow deposition patterns. This approach also suggests a high resilience of pollen grains to water percolation, as they seem to persist on the surface of ablation layers.

4. DISCUSSION AND CONCLUSION

The success of the drillings expeditions and ice core analyses on Alto dell'Ortles and Pian di Neve glaciers demonstrate that ice bodies in the eastern Alps are

capable of retaining information on past climate, environment and human activities. The date of 7 ka, obtained for the basal ice of the Alto dell'Ortles, points to the possible presence of ice older than the Little Ice Age, preserved in the deeper parts of the glaciers. In particular, the idea of dating the deepest layers of Pian di Neve (270 m) is certainly tempting and might lead to unexpected results.

The recent advances in pollen-based chronology for ice core prove that accurate analyses can provide reliable annual to sub-seasonal timescales. Such studies also indicate that pollen grains are not affected by water percolation like other proxies in the ice (e.g. stable isotopes) and therefore tend to accumulate on the ablation surfaces.

Future challenges beyond the presented projects include: i) finding new suitable sites for ice core drilling on the Alps; ii) recovering endangered ice archives; ii) conserving the ice for future studies; iii) establishing a standard approach including environmental and climatic proxies; iv) expanding the range of investigated ice archives to ice caves as a valid complementary palaeo-archive.

The scientific community has already begun to partially address these issues. Garzonio et al. (2018) has made the first step towards the development of a methodology to assess the suitability of Alpine glaciers for ice core drillings, in order to facilitate the collection of cores with a preserved stratigraphy, while the "Protecting Ice Memory" project has started recovering ice cores from mountain glaciers most at risk (in the Alps and the world), and storing them in Antarctica for future generations of scientists.

Finally, the study of ice masses from caves is becoming increasingly important as their suitability for palaeo studies has been recognised. Preliminary palynological studies on such ice archives are ongoing in at least two caves located in the Eastern Alps in the frame of project C3- Cave's cryosphere and climate (https://www.c3project.net) and at the Cenote cave (Santagata et al., 2017).

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REFERENCES

Anzidei A.P., Bulgarelli G.M., Catalano P., Cerilli E., Gallotti R., Lemorini C., Milli S., Palombo M.R., Pantano W., Santucci E. (2012) - Ongoing research at the late Middle Pleistocene site of La Polledrara di Cecanibbio (central Italy), with emphasis on human-elephant relationships. Quaternary International, 255, 171-187.

Bortenschlager S. (1970) - Probleme und Ergebnisse der Untersuchung von Pollenspektren im Hochgebirge (Kesselwandferner, Ötztaler Alpen, 3240 m). Mitteilungen der Ostalpin-Dinarischen Sektion der Internationalen Vereinigung für Vegetationskunde, 10(2), 5-9.

Carturan L., Cazorzi F., Dalla Fontana G. (2012) - Distributed mass-balance modelling on two neighboring glaciers in Ortles-Cevedale, Italy, from 2004 to 2009, Journal of Glaciology, 58, 467-486.

Diolaiuti G., Bocchiola D., D'agata C. Smiraglia C. (2012) - Evidence of climate change impact upn glaciers within the italian Alps. Theor Appl Climatol, 109, 429.

Festi D., Carturan L., Kofler W., dalla Fontana G., de Blasi F., Cazorzi F., Bucher E., Mayr V., Gabrielli P., Oeggl O. (2017) - Linking pollen deposition and snow accumulation on the Alto dell'Ortles glacier (South Tyrol, Italy) for sub-seasonal dating of a firn temperate core. The Cryosphere, 11, 937-48.

Festi D., Kofler W., Buch-er E., Carturan L., Mair V., Gabrielli P., Oeggl K. (2015) - A novel pollen-based method to detect seasonality in ice cores: a case study from the Ortles glacier, South Tyrol, Italy. Journal of Glaciology, 61(229), 815-824.

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., 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., Zennaro P. (2016) - 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.

Gabrielli P., Barbante C., Carturan L., Cozzi G., Dalla Fontana G., Dinale R., Draga G., Gabrieli J., Kehrwald N., Mair V., Mikhalenko V.N., Piffer G., Rinaldi M., Seppi R., Spolaor A., Thompson L.G., Tonidandel D. (2012) - Discovery of cold ice in a new drilling site in the Eastern European Alps. Geografia Fisica e Dinamica Quaternaria, 35, 101-105.

Gabrielli P., Carturan L., Gabrieli J., Dinale R., Krainer K., Hausmann H., Davis M., Zagorodnov V., Seppi R. and Barbante C. (2010) - Atmospheric warming threatens the untapped glacial archive of Ortles mountain, South Tyrol. Journal of Glaciology, 56 (199), 843-853.

Garzonio R., Di Mauro B., Strigaro D., Rossini M., Colombo R., De Amicis M., Maggi V. (2018) - Mapping the suitability for ice-core drilling of glaciers in the European Alps and the Asian High Mountains. Journal of Glaciology, 64 (243), 12-26.

Huss M. (2012) - Extrapolating glacier mass balance to the mountain-range scale: the European Alps 1900-2100, The Cryosphere, 6, 713-727.

Kern Z., Perşoiu A. (2013) - Cave ice - The imminent

loss of untapped mid-latitude cryospheric palaeoenvironmental archives. Quaternary Science Reviews, 67, 1-7.

IPPC (2013) - Climate Change 2013: The Physical Science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker T.F. et al eds. Cambridge University Press, Cambridge, UK and New York, USA, pp. 1535.

Luetscher M., Jeannin P., Haeberli W. (2005) - Ice caves as an indicator of winter climate evolution: a case study from the Jura Mountains. The Holocene, 15, 982-993.

Picotti S., Francese R., Giorgi M., Pettenati F., Carcione J. M. (2017) - Estimation of glaciers thickness and basal properties using the horizontal to vertical spectral ration (HVSR) technique from passive seismic data. Journal of Glaciology, 63 (238), 229-248.

Santagata T., Sauro F., Spötl C., Festi D., Oeggl K., Dal Molin L., Kadded F., Camorani M., Romeo A. (2017) - The Cenote Project: monitoring a high-altitude ice cave in the Dolomites, Italy. Proceedings of the 17th International Congress of Speleology, 86-88.

Vareschi, V. (1934) - Pollenanalysen aus Gletschereis. Ber. Geobot. Inst. Rübel, 81-99.

von Gunten H. R., Rössler E., Gäggeler H. (1982) - Dating of ice cores from Vernagtferner (Austria) with fission products and lead-210. Zeitschrift fuer Gletscherkunde und Glazialgeologie, 1, 37-45.