Dear editor,

Thank you for your response and the chance to clarify our previous response. Please find attached the revised version of the article, as well as the responses to reviewers, with our comments in red (in the submitted version, it was not clear where or responses starts). We did address all queries at length (especially the ones of reviewer #1), included the suggested references and also expanded the discussion on ice formation and stable isotopes in ice (including reference to the Sancho et al., 2018 paper). The manuscript was thoughtfully checked and corrected by two native speakers of English (one by a Sr lecturer in the UK, dr. Simon Hutchinson, who also suggested a slight rearrangement of the title).

We are looking forward to the comments of the reviewer on the new version of the text.

Dear reviewers,
On behalf of the authors, we thank you for the time spent on reading our article and for the constructive comments. In the attached document we present our point-by-point responses (in red) to the comments and the subsequent modifications of the text.

Response to reviewer #1
1) The preselection of the samples entered or excluded from age-depth modelling needs additional consideration. It is written in Table 1 that the sample collected at 63 cm was a fragment of a large wood. It was recently discussed that there is a notable risk related to the C-14 dating of large wood fragment because they can origin from reworked trunks so their radiocarbon age could predate the actual age of the hosting ice layer (Kern 2018). The C-14 age of sample at 63 cm shows the most pronounced old bias, so I think it is an example of the above discussed situation and there is a good reason to omit the obtained C-14 age from age-depth modelling.
Kern, Z. (2018) Dating cave ice deposits. In: Persoiu, A. and Lauritzen, SE (eds) Ice Caves, Elsevier pp.109-122.
Indeed, dating cave ice deposits is extremely challenging, due to possible incorporation of young organic material in old ice (during melting) or viceversa, redeposition of old organic material in young ice. As correctly pointed out by the reviewer, this was the reason behind rejecting the sample at -63 cm.

2) Comparing the new C-14 ages to an independent set of C-14 ages (Maggi et al., 2009) is principally a good idea. However, as fa as I know, the ice core of Maggi et al., 2009 was extracted in May 2004. I am pretty sure that the equal depth values below the ice surface in 2004 and in 2014 do not represent the same stratigraphic situation. There are two factors which should be considered: - Basal melting has been documented practically at each major cave ice block where it was monitored. Assuming a similar basal melting rate as reported from the nearby Scarisoara Ice Cave (1.54 cm/yr, Persoiu 2005) ~15.4 cm should be subtracted from the depth belonging to the C-14 ages of the samples collected in 2004 before the two set of ages are compared. Negative mass balance at the ice surface over the past decades has been reported practically from all cave ice deposits in Europe. For instance, in the previously mentioned Scarisoara Ice Cave the complete loss of 20 century ice accumulation was assumed (Persoiu et al., 2017). I think it is very likely that some degree of surface melting took place also in the Focul Viu Ice Cave during the past decades. The difference between the 2004 and 2014 ice levels should be quantified and it should be used to establish a corrected depth scale before the two set of ages are compared.
We thank the reviewer for this comment; we did ponder ourselves for long on the age of ice. We will discuss basal and surface melting separately.
First, the depths along both cores (“Maggi core” and ours) were measured from the 2004 and 2016 ice surfaces, respectively (one of us - AP - was involved in both drilling efforts). We mention this, because the position of a certain horizon inside a cave glacier can be measured both against the ice surface at the time of drilling or against a fixed point on the cave’s walls/ceiling (a situation not encountered in polar and most mountain glaciers). As such, if a horizon at a certain depth is measured several years later, its depth below the ice level will be affected by changes at the surface only (melting or accumulation), whereas the same depth below the cave’s ceiling will be affected by changes at the surface and also by the general lowering of the ice block due to basal melting (lateral flow, although present for example in Scărișoara Ice Cave (Romania) and Dobsinska Ice Cave (Slovakia), has a very limited role on lowering the ice surface against a fixed point).
Now, the ages reported by Valter et al (2009) were measured against the 2004 surface, whereas ours were measured against the 2016 surface. The surface of the ice block was affected by melting and accumulation processes between these two dates, but we have no means to quantify them (see also the response below). We can only make assumptions on how much ice melted or how much accumulated. Our data from Scărișoara (as pointed put by the reviewer) shows that all the ice that accumulated since ~1860 AD melted away, most of this melting occurring between AD 1947 (when monthly measurements in the cave started) and ~AD 1982 (this was due to changes in the cave’s morphology, with ice levels being ± constant since). Contrary, tritium data from the nearby Borțig Ice Cave (Kern et al., 2009) indicates no important melting since at least AD 1950.

Summing up this information, we conclude:
1. Basal melting resulted in the lowering of horizons dated by Maggi et al (reported in 2009, drilled in 2004) compared to the cave ceiling, but did not result in changes between the depths measured by them and the surface of ice
2. Depth along the core drilled in 2016 (this study) were measured against the 2016 ice surface, and very likely this was not the same as the 2004 surface.
Consequently, we agree that numerous assumptions would be required to combine the two chronologies. Based on our knowledge of cave ice processes and dynamics and assuming "normal" melting conditions between 2004 and 2016, we estimate that the depths reported by Maggi et al in 2009 should now be some 10-20 cm lower (for example, the depth of sample SO5-13 reported by Maggi et al at 213 cm below the 2004 surface would now be at ~193 cm below the 2016 surface, exactly matching our depth-age model. The same would also be true for Maggi's sample SO9-5. The other samples by Maggi et al (wood samples) are already outside our depth-age model. Now, at this point we are facing two possibilities: 1) incorporate Maggi's ages in our depth-age model and thus improving it by increasing the number anchoring points and 2) use Maggi's ages to independently support or model ("all depth-age models are wrong…"). We tested the first possibility and the change in the modeled ages was between 0 and 30 years, thus within the limits of the dating uncertainty. Nevertheless, we did lose the independent verification of our model and therefore we decided to keep the depth-age model as is, except modification of the topmost age (see p. 3 below).

3) As an additional consequence of the above mentioned surface melting (i.e. negative mass balance at the ice surface) the collection year should not assign to the top of the core during the age-depth modelling.
We agree, up to a point. While we do not have detailed monitoring data from the cave, observations made during (almost) annual trips show that in some years melting affects more ice that has accumulated in the previous winters, while in others, less. Accordingly, it is impossible to precisely establish the age of the upper (most recent) layers of ice (well, technically, before melting starts during the summer of a given year, the age of the uppermost layer of ice is exactly that of the year, being formed in the previous winter). Monthly measurements in the nearby Scărişoara Ice Cave (with pauses, since 1947) have shown that annual melting could result in the loss of up to 20-25 years worth of ice accumulation. Our observations have shown that the two caves (~10 km apart, same elevation, same morphology of the cave and ice block) behave similarly in terms of response to external climate (qualitatively, but perhaps not quantitatively). Consequently, while assigning a modern age for the topmost layer of ice is wrong, it would be equally wrong to assign any other age in the absence of precise age determination. For simplicity (Occam's razor) we keep a modern age of this layer. However, the top age for the depth 0 cm is now modeled as a uniform distribution between 1991 and 2016 AD, allowing for a 25 years' time interval. This range is similar to that of the radiocarbon-based ages and it also reflects the uncertainty related to the melting – see above.

4) Finally a comment on the presentation and discussion of the model ages: Keeping in mind that the uncertainty of model ages ranges from ~10 to ~40 yrs (according to fig6) reporting dates with annual precision (e.g., P4 L14 "...the maximum age of the ice is . . .1099 cal BP. . .", P3L17 "ice accumulation rate between AD851 and 947") is misleading. Please round the modeled dates to the nearest decade and refrain presenting the model dates with annual precision.
We rounded all ages throughout the text to the nearest decade (and in some case, half-decade).

Page2 Line7 Colucci et al., 2016 and Colucci & Guglielmin 2019 could be cited also to support this statement.
The statement was actually discussing the influence of the AMO on climate in Europe, not specifically on cave ice. We have nevertheless added a sentence to the introduction " Studies of ice caves in southern Europe have also highlighted the sensitivity of cave glaciers to summer climatic conditions (Colucci and Guglielmin, 2019; Colucci et al., 2019".

Page2 Line8 The statement "In such caves, ice is deposited as layers of frozen water..." needs revision. This is not the only origin of ice in temperate climatic region. Mavlyudov 2018 can be recommended as a recent review on ice genesis and types of ice caves.
Of course. We have changed the text and now it reads (see also the response to the first comment by rev 2): "In such caves, ice forms either by freezing of water or direct snow deposition in the entrance shafts (e.g., Mavlyudov, 2018). […] Regardless of the deposition style, the ice records the original stable isotope composition of precipitation that further reflects changes in air temperature and thus is an important archive of past temperature and moisture source variability".

P3L13 "mL" instead of "ml"
Corrected.

P3L15-18 This part is neither drilling nor stable isotope analysis. You should move this paragraph to another place or change the title of the subsection, please.
We added a new paragraph entitled "3.3 Climate data" and moved the text of climate-related analytical methods there.
P3 L31-32 probably better to say that small carbon yield instead of small sample mass was the problem for AMS analysis

Indeed, carbon yield sounds more proper here.
Corrected.

P5 L9 I think the citation in this line should be Nagavciuc et al, 2019b
Yes. Corrected.

P5 L39 The current statement is triviality. The AMO index is indeed strongly associated with the prevailing SST since it is defined based on the SST pattern. The sentence needs revision.
Yes. We have deleted the redundant part of the sentence and modified the text: “Further, we have computed the correlation map between the summer mean air temperature at SB station (with the longest instrumental record) and the summer SST as indicator of AMO variability (Sutton and Dong, 2012).”

P5 L42 Probably “the” instead of “de”
Corrected

P6 L9-10 Please consider replacing “at our site location” with the excat site information e.g.”in cave ice deposit in the FV ice cave” to avoid any potential confusion.
Indeed. The text now reads “high δ18O values in the FV ice core”

P7 L5 probably “maxima” instead of “maxim”
Corrected

P7 L7-9 Cited references need some revision here. Moberg et al 2005 is not a summer temperature reconstruction; Seim et al., 2012 is again not a pertinent reference because there is no summer temperature reconstruction in the study. Finally, I’ve comment on the citation of Dragusin et al., 2014. The sentence lists warm decades, however the temporal resolution of speleothem record of Dragusin et al. 2014 is insufficient for the past 1000yrs to be able to see decadal warm peaks.
Finding seasonally distinct climate proxies is always difficult and we thank for the suggestions of the reviewer. First, we have removed the reference to Drăgușin et al. (2014), due to the very low temporal resolution of the record during the investigated period. Further, we have used the Moberg et al (2005) data as it summarizes both high resolution records biased towards the growing season (summer), and low-resolution ones that include several summer records (Moberg et al., 2005). However, not being specifically a summer temperature record, we have decided – as suggested by the reviewer – to eliminate it. Seim et al (2012) – while not specifically a temperature record, it is nevertheless the result of the combination of summer precipitation and temperature climatic conditions, i.e., summer droughts (Seim et al., 2012). Our present and previous work (Nagavciuc et al., 2019a, cited in the main text) shows that both Western Romania (where Focul Viu Ice Cave is located) and Albania (from where the Seim et al data originated) are influenced to the same extent by the AMO and summer droughts and thus we have used this record in our analysis. Figure 7 has been modified accordingly, by removing the Drăgușin et al (2014) and Moberg et al (2005) records, but we have kept the Seim et al (2012) record and changed the caption to specify that it is a summer drought record.

P7L13 “with” instead of “woth”
Done

There are some easily correctable small mistakes or strange points in the reference list: -There are few places where the text is in red for a few characters (P10L6, P11L20) -P11L7 a space is missing between “and” and “predicting”
Corrected

The figures are clear and illustrate well the paper however if Authors accept my suggestions on age-depth modelling then Fig2 should be modified.
Please see our first comments on depth-age modeling.

In the caption of Fig7 (P19 L5) probably “Northern Hemisphere” should be written instead of “Nordic Hemisphere”
Done

Table1: First and foremost, the typo in the title should be corrected (“Table” instead of “Tabel”).
Done

-9th column: Please follow recommendations of Millard 2014 reporting calibrated ages and present all calibrated intervals with associated probability.
Corrected.

-10th column: The current header sounds strange. Please revise. In addition, the ±sign suggests that accompanied uncertainties are also presented in the cells but it is not mentioned neither in the title nor in the header. Finally, the header suggests mean model ages are presented. Why did you used mean age? According to my experience using median ages, which belong to the highest probability, is more usual.

Indeed, for interpretation of separate probability age distributions the median would be more suitable. However, the ages modelled by P_Sequence have all normal distribution. In fact, this assumption is made in the underlying statistical algorithm (Bonk Ramsey 2008, Appendix, p. A.2.3). As such, the modeled ages are calculated as means and standard deviations. We clarified it in the table header.

Response to reviewer #2

Besides comments directly highlighted in the corrected pdf, I have only one point that in my opinion could/should be better addressed. What is missing is a wider discussion com- paring other results recently obtained in ice cave core campaigns conducted in other regions of Europe. For instance, a very recent and interesting paper by Sancho et al. 2018 "Middle-to-late Holocene palaeoenvironmental reconstruction from the A294 ice-cave record (Central Pyrenees, northern Spain)" gives interesting results in high- lighting a link with NAO in this area. Do you think there could be or there is also a link with the NAO in the ice accretion of this cave ? The paper would benefit in terms of interest for a wider audience if comparison with other studies will be presented from ice cave coring programs. The ice cave community is not so big and thus not many papers dealing with such evidence exist. It wouldn't be a huge effort to discuss other results in this field, but a great improvement to the paper with a small commitment

Indeed, there are but a very few reconstructions of pats climate variability, and the one by Sancho et la (2018) is singular in Western Europe. We have deliberately left this record out of discussion as we 1) were focusing on summer climate variability and 2) strongly support analysis of paleoclimate records not by archive or proxy type, but by the climate variable they are recording and the season these variables represent. The ice in the A294 cave records winter climate conditions (the ice in the cave formed by snow diagenesis (and to a lesser extent water freezing), strongly influenced by NAO variability. Now, the NAO is influencing European climate during winter (Hurrel et al., 1995; Bojariu and Paliu, 2001), having an almost imperceptible influence of summer climatic conditions (also some annually-sensitive records "see" the NAO influence, likely due to the fact that they incorporate winter signals). Nevertheless, we have expanded the introduction to include information on more ice-caves studies. The text now reads:
"In such caves, ice forms either by freezing of water or direct snow deposition in the entrance shafts (e.g., Mavlyudov, 2018). Several studies have shown that these deposits host a wealth of information on past climate variability. Thus, Perșoiu et al. (2017) and Sancho et al. (2018) have shown that proxies in cave ice forming during winter months record changes in temperature and moisture sources, likely influenced by the dynamics of the North Atlantic Oscillation. Other studies have used pollen and plant macrofossils recovered from cave ice to reconstruct past vegetation dynamics (Feurdean et al., 2011; Leunda et al., 2018) while others used the accumulation rate of ice as indicators of past climatic variability (e.g., Kern et al., 2018) or atmospheric processes (Kern et al., 2009). Studies of ice caves in southern Europe have also highlighted the sensitivity of cave glaciers to summer climatic conditions (Colucci and Guglielmin, 2019; Colucci et al., 2019, Perșoiu et al., 2020). "

P1 L31 – I would say that temperature and precipitation are of course important, but specifically the ones we have for the longest period. . . other parameters would be important as well, but we don't possess long records

Yes, indeed. We have changed the text: "Especially important are high-resolution reconstructions of the past variability of different climatic variables – seasonal air temperatures, precipitation amounts, moisture sources – that allow for direct comparisons with the dynamics of natural forcing and further deciphering the mechanisms of past and present climate dynamics."

P2 L15-20 Here the authors already give conclusions. . . I would prefer to read here the goals of this work and find the conclusions at the end of the manuscript

We have rephrased the text according to the suggestion. It now reads: "Here, we present a reconstruction of summer climate variability and large-scale circulation drivers during the last 1000 years in East Central Europe based on the δ^{18}O and δ^{2}H values measured along an ice core drilled in Focul Viu Ice Cave (Western Carpathian Mountains, Romania).

P4 L 30 Precipitation and not Precipitations

Corrected

P4 L37 it is "now", "low" or "no" winter accumulation ? I guess it is "low", in such a way the sentence is reasonable

Typo. Corrected to “no” from “now” so that the text reads “no inflow of water and thus no winter ice accumulation”. The point here is that ice in winter forms as dripping water freezes to form layers of ice on top of the existing ice block. Cold winters result in frozen soils and cap rock above the cave and hence no infiltration, resulting in lack of winter ice accumulation.

Figure 1a - letters and font are too small, impossible to read them... omit "Mts" for the mountan chains which is unuseful
We have corrected figure 1.

Figure 5 legend of scale is missing
Thank you for spotting this, we added the legend.

In addition to these corrections we have updated and visually improved all figures and the spelling and grammar of the main text was checked and corrected by a native speaker of English.

References cited (apart from those cited in the main text)

Bojariu, R. & Paliu, D. NAO projection on Romanian climate uctuations in the cold season In Detecting and Modelling Regional Climate Change and Associated Impacts (eds Brunet, M. & Lopez Bonillo, D.) 345–356 (Springer, 2001).

Hurrell, J.W.,Kushnir,Y.,Ottersen,G.&Visbeck,M.An overview of the North Atlantic Oscillation In North Atlantic Oscillation: Climatic Significance and Environmental Impact-Geophysical Monograph 134 (eds Hurrell, J. W., Kushnir, Y., Ottersen, G. & Visbeck, M.) 1–35 (American Geophysical Union, 2013).

Kern, Z., Molnár, M., Svingor, É., Persoiu, A., and Nagy, B.: High-resolution, well-preserved tritium record in the ice of Bortig Ice Cave, Bihor Mountains, Romania, The Holocene, 19, 729-736, https://doi.org/10.1177/0959683609105296, 2009.

Cave ice s~~S~~table isotopes ~~in cave ice ~~suggest summer temperatures in East-Central Europe link~~are linked ~~ to AMO variability

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Abstract. The climate of East-Central Europe (ECE) is the result of the combination of influences originating in the wider North Atlantic realm, the Mediterranean Sea and Western Asia/Siberia. Climate models suggest that these competing influences will result in difficult to predict responses to ~~the ~~ongoing climatic changes, thus making mitigation and adaptation strategies challenging to devise and implement. Previous studies have shown that the complex interplay between the large-scale atmospheric patterns across the region result in strongly dissimilar summer and winter conditions on time scales ranging from decades to millennia. To put these into a wider context, long term climate reconstructions are required, but, largely due to historical reasons, these are lacking in ECE. We address these issues by presenting a high resolution, precisely dated record of summer temperature variations during the last millennium in ECE, based on stable isotopic analysis performed on a 4.84 m long ice core extracted from Focul Viu Ice Cave (Western Carpathians, Romania). The data shows little summer temperature differences between the Medieval Warm Period (MWP) and the Little Ice Age (LIA) on centennial scales, but with well-expressed minima and maxima, which occurred synchronously with periods of low and high solar activity. Further, summer temperatures fluctuated with a periodicity similar to that of the Atlantic Multidecadal Oscillation~~,~~ suggesting that solar variability-induced climatic changes were transferred locally by atmospheric processes. Contrary to summer temperatures, winter ones show stronger contrast between the MWP and LIA, thus suggesting that the later were likely an expression of winter climatic conditions.

1 Introduction

R~~The r~~apid global warming (IPCC, 2018) and the ensuing suite of climatic changes that it triggers (Coumou and Rahmstorf, 2012) demands a clear understanding of the background mechanisms ~~behind them ~~in order to be able to disentangle natural and anthropogenic processes (Haustein et al., 2017; IPCC, 2018). Especially important are high-resolution reconstructions of the past variability of ~~specific ~~different climatic variables – seasonal air temperatures,~~ and~~ precipitation amounts, moisture sources ~~being the most important –~~ that allow for direct comparisons with the dynamics of natural forcing and further deciphering the mechanisms of past and present climate dynamics. The last 1000 years are particularly significant, as the European climate changed from, generally, warm to cold (the Medieval Warm Period-Little Ice Age transition, Jones et al., 2009) and back to warm (the present-day warming, Neukom et al., 2019). T~~ and t~~hese transitions allow for testing the links between forcing and climatic response. While several global (Jones and Mann, 2004; Mann et al, 2009) and hemispheric (Moberg et al, 2005; Neukom et al., 2019; PAGES 2k Consortium, 2019; Ljungqvist et al., 2019) climatic reconstructions have been published, these made no seasonal differentiation – a task that became recently increasingly necessary to constrain ~~the ~~seasonally distinctive climatic changes (e.g., Ljungqvist et al., 2019), as these are responding to different forcing mechanisms (e.g., Perșoiu et al., 2019). On multidecadal time scales, summer climate over Europe is influenced, mainly, by the Atlantic Multidecadal Oscillation (AMO). The AMO is a climate mode of variability associated with periodic~~al~~ anomalies of sea surface temperatures (SSTs) in northern, extratropical latitudes. The positive phase is characterized by positive SST anomalies spanning the whole North Atlantic Ocean and is associated with above normal temperature over the central and eastern part of Europe, while the negative phase is characterized by negative SST anomalies over the North Atlantic Ocean and is associated with below normal temperatures over the central and eastern part of Europe. Over Europe the influence of the AMO is clearest during ~~the~~ summer (Sutton and Dong, 2012; Ioniță et al., 2012; 2017; O'Reilly et al., 2017).

In temperate climatic region, one of the most sensitive environmental archives are ice caves (Homlund et al., 2005, Kern and Perșoiu, 2013), i.e., rock-caves hosting perennial accumulations of ice. In such caves, ice forms either by freezing of water or direct snow deposition in the entrance shafts (e.g., Mavlyudov, 2018). Several studies have shown that these deposits host a wealth of information on past climate variability. Thus, Perșoiu et al. (2017) and Sancho et al. (2018) have shown that proxies in cave ice forming during winter months record changes in temperature and moisture sources, likely influenced by the dynamics of the North Atlantic Oscillation. Other studies have used pollen and plant macrofossils recovered from cave ice to reconstruct past vegetation dynamics (Feurdean et al., 2011; Leunda et al., 2019) while others used the accumulation rate of ice as indicators of past climatic variability (e.g., Kern et al., 2018) or atmospheric processes (Kern et al., 2009). Studies of ice caves in southern Europe have also highlighted the sensitivity of cave glaciers to summer climatic conditions (Colucci et al., 2016; Colucci and Guglielmin, 2019; Perșoiu et al., 2020). Regardless of the deposition style, ~~is deposited as layers of frozen water, that carr~~the icey records ~~with them~~ the original stable isotope composition of precipitation that further reflects changes in air temperature and thus ~~are~~ is an important ~~proxies~~ archive of past temperature and moisture source variability (Perșoiu et al., 2011a, 2011b). ~~In such caves, ice forms by the freezing on infiltrating water, the later accumulating during the rainy season, between early summer and late autumn (depending on site-specific conditions).~~ The Carpathian Mountains host several ice caves (Brad et al., 2018) that preserve a large variety of geochemical information on past climate and environmental changes (Fórizs et al., 2004; Kern et al., 2004; Citterio et al., 2005; Perșoiu et al., 2017). Here, we present ~~the first reconstruction of~~a reconstruction of summer climate variability and large~~-~~scale circulation drivers during the last 1000 years in East Central Europe based on the δ^{18}O and δ^{2}H values measured along an ice core drilled in ~~in~~ Focul Viu Ice Cave (Western Carpathian Mountains, Romania). ~~We argue that the stable isotope composition of cave ice is a proxy for summer air temperatures, and show that during the past millennium changes in these climatic parameter were mainly the result of external forcing induced by the variability of the AMO. Further, we show that summer temperatures in Eastern Europe were generally stable during the past 1000 years, the MWP-LIA differences being induced by high winter temperature variability.~~

2 Site information

Focul Viu Ice Cave (FV, 107 m long, ~30 m deep) is located in the Central Bihor Mountains, Romania (46.27º N; 22.68º E, 1165 m above sea level, Fig. 1a, Perșoiu and Onac, 2019). The cave has a simple morphology (Fig. 1b, 1c)~~,~~ with a small entrance that opens into the Great Hall (68 × 46 m), which, in turn, is followed by a narrow gallery~~, the(~~ Little Hall, ~~(~~20 × 5 m). The ceiling of the Great Hall opens to the surface (Fig. 1c)~~,~~ allowing ~~for direct~~ precipitation to reach the cave. Below the opening, and covering the entire surface of the Great Hall,~~;~~ a layered ice block has developed, with an estimated thickness of 20 m and minimum volume of 30,000 m^3 (Orghidan et al., 1984; Brad et al., 2018). The descendent morphology of the cave and the presence of the two openings determine ~~a specific~~ air circulation (Perșoiu and Onac, 2019), with cold air inflow through the lower entrance and warm air outflow through the upper one in winter, and slow convective circulation within the cave (with no air mass exchange with the exterior) during summer. As a ~~consequence~~ result of this air circulation, between

October and April the dynamics of air temperature ~~the cave has a specific climate, with negative temperatures following~~ inside and outside of the cave follow a similar pattern~~the external ones~~ while between May and September ~~between October and April, and~~the temperatures are stable ~~ones~~ at 0 °C~~ between May and September, when ice melts and absorbs the heat transferred to the cave's atmosphere by conduction through the air and rock~~.

A direct consequence of the predominantly negative air temperatures in the cave is the genesis, accumulation and preservation of ice (Fig. 1b, 1c). During summer, infiltrating rainwater accumulates on top of the existing ice block and at the onset of negative temperatures in September it starts to freeze~~,~~ forming a 1-20 cm thick layer of ice. Infiltration and subsequent freezing of water during warm periods in winter ~~adds supplemental~~results in additional layers of ice on top of the ice block.~~ , however, a~~At the onset of melting in April/May, this winter ice melts~~ away~~. The result of these processes is a multiannual, layered, ice block, consisting of annual couplets of clear ice (on top) and a sediment-rich layer beneath~~sediment reach debris ones (at the bottom)~~. Inflow of warm water in wet summers ~~could result~~leads to~~ in the~~ rapid ablation of the ice at the top of the ice block, ~~thus~~ partly altering the annual layering~~ of the ice block~~. The processes ~~behind~~ of cave ice formation by water freezing and the registration of environmental signals by various proxies (e.g., stable isotope composition of ice, pollen content~~ etc~~) have been described from the nearby Scărișoara Ice Cave (Perşoiu and Pazdur, 2011; Feurdean et al., 2011) and, given the ~~close~~ similarities between the two caves, are also pertinent ~~for~~ to Focul Viu Ice Cave~~, as well~~. The one notable difference is the timing of the onset of freezing: in Scărișoara Ice Cave, the onset of freezing is delayed until late-autumn and early winter (Perşoiu et al., 2017), whereas in Focul Viu Ice Cave it starts in early autumn.

3 Methods

3.1 Drilling and stable isotope analyses

The FV ice core (4.87 m long, 10 cm diameter) was drilled in May 2016 from the Great Hall of FV Ice Cave (Fig. 1d) using a modified PICO electric drill (Koci and Kuivine, 1984) manufactured by Heavy Duties S.R.L, Cluj Napoca, Romania. The ice core was cut into 1 cm~~ thin~~ layers ~~(~~considering also the annual layering~~)~~ in ~~the~~ a cold room, except for the section between 290 and 320 cm below surface, where we intercepted a tree trunk. Each sample~~s~~ was sealed in a plastic bag~~s~~, allowed to melt at room temperature, transferred to a 20 mL~~l~~ HDPE scintillation vial~~ s~~ and stored at 4 °C prior to analysis.

Precipitation samples were collected monthly between March 2012 and December 2018 at Ghețar (GT, 46°29'28.45" N, 22°49'26.02" E, 1100 m asl, ~15 km SE of the location of FV Cave) using collectors built according to IAEA specification.

~~The sea surface temperature (SST) is extracted from the Extended Reconstructed Sea Surface Temperature data (ERSSTv5) (Huang et al., 2018). This dataset covers the period 1854 – present and has a spatial resolution of 2° x 2°. The AMO index used in this study has been obtained from https://climexp.knmi.nl/data/iamo_ersst_ts.dat and is based also on the ERSSTv5 data set.~~

Water samples were analyzed for stable isotope composition at the Stable Isotope Laboratory, Ștefan cel Mare University (Suceava, Romania), using a Picarro L2130*i* CRDS analyzer connected to a high precision vaporizing module. All samples were filtered through 0.45 µm nylon membranes before analysis and manually injected into the vaporization module multiple times, until the standard deviation of the last four injections was less than 0.03 for $\delta^{18}O$ and 0.3 for $\delta^{2}H$, respectively. The average of these last four injections was normalized on the SMOW-SLAP scale using two internal standards calibrated against VSMOW2 and SLAP2 standards provided by the IAEA and used in our interpretation. A third standard was used to check the long-term stability of the analyzer. The stable isotope composition of oxygen and hydrogen are reported using standard δ notation, with precision estimated to be better than 0.16 ‰ for $\delta^{18}O$ and 0.7 ‰ for $\delta^{2}H$~~,~~ respectively, based on repeated measurements of an internal standard.

3.2 Radiocarbon dating and age-depth model construction

The wide opening to the surface in the ceiling of the Great Hall ~~The wide skylight above the Great Hall~~ (Fig. 1c) allows for a large volume of organic matter to fall into the cave and ~~be~~ subsequently become trapped in the ice. During drilling, we ~~have~~ recovered over 40 samples of organic matter from large tree trunks to pieces of leaves. Only 14 were suitable for radiocarbon dating, ~~out~~ of which 2 were not datable due to their extremely small ~~sample mass~~carbon yield. AMS radiocarbon analyses were performed at the Institute of Physics, Silesian University of Technology, Poland (Piotrowska, 2013). All ~~of the~~ samples were precleaned with standard acid-alkali-acid treatment, dried and subjected to graphite preparation using an AGE-3 system (~~by~~ IonPlus, CH) equipped with an Elementar –VarioMicroCube ~~by Elementar~~ elemental analyzer and automated graphitization unit (Wacker et al., 2010; Nemec et al., 2010). The ^{14}C concentrations in graphite produced from unknown samples, Oxalic Acid II standards and coal blanks ~~have been~~were measured by the DirectAMS laboratory, Bothell, USA (Zoppi et al., 2007). The results are reported in Table 1. The radiocarbon dates ~~have been~~were ~~subjected to~~ calibrated~~ion with the use of~~using OxCal v4.3 (Bronk Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013). The ~~or~~ NH1 curve (Hua et al., 2013) was used for one post-bomb date.

Because ~~the~~ organic material can fall into the cave decades to centuries before being trapped in the ice (see Fig. 1b), we have carefully screened the radiocarbon results prior to age-depth modeling with the aim ~~to~~ of selecting the most reliable dates forming a chronological sequence and not contradict the previously well-dated core reported by Maggi et al. (2008). In total, four dates were selected for age-depth modeling. For the top of the ice core a uniform age distribution from [illegible] to 2016 AD was assigned, allowing for the possibility of surface ice melting.~~and a collection year AD 2014 was assigned for the top of the ice core.~~ The model was constructed using the OxCal *P_Sequence* algorithm (Bronk Ramsey, 2008) with variable prior *k* parameter (*k*=1, U(-2,2); Bronk Ramsey and Lee, 2013) and extrapolated to ~~the~~ a depth of 4.86 m. The agreement index of the model was ~~83.1~~85 %, confirming a good statistical performance when the threshold of 60 % is surpassed. The sections between the dated depths were assumed to have a constant deposition rate. The complete age-depth model is shown in Fig. 2. For further analysis the mean age derived from the model was used and is also~~,~~ reported ~~also~~ in Table 1.

3.3 Climate data

The sea surface temperature (SST) is extracted from the Extended Reconstructed Sea Surface Temperature data (ERSSTv5) of Huang et al. (2018). This dataset covers the period 1854 – present and has a spatial resolution of 2° x 2°. The AMO index used in this study has been obtained from https://climexp.knmi.nl/data/iamo_ersst_ts.dat and is based also on the ERSSTv5 data set. The station-based meteorological data was provided by the Romanian National Meteorological Administration.

4 Results and discussions

4.1 Ice accumulation in Focul Viu Ice Cave

The results of the radiocarbon analyses performed on organic matter recovered from the ice are shown in Table 1~~,~~ with the ~~depth-age~~age-depth model shown in Fig. 2. The maximum age of the ice is 1000~~26~~±20 cal BP at 4.45 m below surface, ~~(~~based on direct dating of organic remains~~)~~ and ~~1099~~ 1100 cal BP at 4.86 m below surface (extrapolation). A rock embedded in the ice at 4.87 m below the surface stopped the drilling effort, but previous work in the cave has shown that the thickness of the ice block exceeds 15 m (Orghidan et al., 1984; Kern et al., 2004; Perşoiu and Onac, 2019).

The ice accumulation rate was 0.39-0.41 cm/year between AD 850~~1~~ and 950~~47~~, 0.29-0.37 cm/year between AD 950~~2~~ and AD 1000~~5~~, 0.36-0.38 cm/year between AD 1010 and AD 1215, 0.4-0.44 cm/year between AD 1220 and AD 1970, and 0.56 cm/years in the past 40 years, with an average of 0.42 cm/year for the entire ice core. The variability seen in the ice accumulation rate during the last 1000 years results from the variable processes involved in the growth and decay of cave ice. Ice can melt as a result of either warm summers with enhanced conductive heat transfer to the cave or wet summers, with rapid ablation resulting from water flowing ~~on top~~across the top of the ice block. Subsequently, ice growth is influenced by the amount of water ~~existing~~ ăr[illegible]at the onset of freezing, the timing of this onset ~~(earlier or later in the year)~~ and its duration. Thus, the resulting accur[illegible]on rate is a record of the complex interplay of these climatic conditions, being an indicator of both ice growth and melt. The ~~relatively (compared to the ensuing periods)~~ high accumulation rates registered between AD 810 and AD 1230 were likely the result of ~~high amounts~~greater amounts of water available in the cave ~~,~~ ~~resulting from~~during the generally wet conditions ~~during~~ of the Medieval Warm Period (Feurdean et al., 2015). The ~~period with the~~ highest accumulation rates were recorded~~of ice occurred~~ between AD 1230 and AD ~~1392~~1400, a period of enhanced Mediterranean moisture transport to the site and slightly warmer winters compared to the preceding and ensuing periods. ~~We tentatively suggest that during this period, the enhanced autumn precipitations originating from the Mediterranean Sea, as evidenced by the high d-excess values in the Scărișora Ice Cave record (Perșoiu et al., 2017) and the warm (and thus likely short) winters led to a deeper lake on top of the exiting ice block at the onset of the freezing period and thus to a high accumulation rate.~~ After AD 1400, palaeoclimate records from the region indicate an abrupt increase in ~~(~~summer~~)~~ precipitation of Atlantic origin (Feurdean et al., 2015) and drop in winter temperature (Perșoiu et al., 2017) likely causing rapid and sustained summer melting and early onset of freezing, thus resulting in an abrupt reduction of net ice accumulation. After AD 1450, the climate in the region was dominated by dry ~~(but with frequent storms)~~ summers with frequent storms and cold winters (Perșoiu, 2017). These~~,~~ conditions ~~that translate~~lead ~~in~~ to low amounts of water available for freezing in early autumn~~, no inflow of water~~ and thus no~~w~~ winter ice accumulation ~~and~~ as well as enhanced summer melting, a combination— of processes ~~translating~~ resulting in minimal ice accumulation ~~rates~~.

4.2 Stable isotopes in Focul Viu cave ice - proxy for summer air temperatures and AMO variability

The variability of $\delta^{18}O$ ~~(~~and $\delta^{2}H$~~)~~ in precipitation at Ghețar, ~~(~~10 km south of the cave's location and at the same altitude~~)~~, assessed for the 2012-2017 period, follows that ~~in~~ of temperature (Fig. 3a), with the maximum values (-3.6 ‰ and -26 ‰, for $\delta^{18}O$ and $\delta^{2}H$, respectively) in July/August and ~~the minimum ones~~minimum (-19.8 ‰ and -140 ‰, for $\delta^{18}O$ and $\delta^{2}H$, respectively) in January. Similar result ~~have been~~were found by Bojar et al. (2009) and Ersek et al. (2018) for the same region, suggesting that the $^{18}O/^{16}O$ ~~(~~and $^{2}H/^{1}H$~~)~~ ratios in precipitation register~~s~~ temperature changes on a regional scale. The Local Meteoric Water Line, defined by the equation $\delta^{18}O = 7.4*\delta^{2}H + 6.1$ (Fig. 3b), has a slope and intercept ~~nearly~~ very similar ~~with~~ to those ~~of~~ found by Ersek et al~~.~~ (2018). Precipitation in the region is mainly delivered by weather systems carrying moisture form the Atlantic Ocean, with the Mediterranean Sea contributing moisture during autumn and winter (Nagavciuc et al, 2019b). The deuterium excess in precipitation (*d-excess* or d) ~~in precipitation~~, defined as $d = \delta^{2}H - 8*\delta^{18}O$ (Dansgaard, 1964) allows for a clear separation of the ~~two types of~~ air masses:~~;~~ Atlantic ocean (d-excess ~~its values being~~ close to the global average of 10 (Craig, 1961)) ~~for moisture sourced from the Atlantic Ocean, and between 12 and 17, for moisture sourced in the~~and the Mediterranean Sea (d-excess between 12 and 17, resulting from the high evaporative conditions in the Eastern Mediterranean Sea). Similarly high values of *d-excess* have been measured by Drăgușin et al. (2017) in precipitation in ~~SW~~ southwest Romania and Bădăluță et al. (2019) in precipitation in ~~NE~~ northeast Romania~~,~~ and linked to air masses originating in the strongly evaporated Mediterranean and Black seas, respecti[illegible]

The FV $\delta^{18}O_{ice}$ and $\delta^{2}H_{ice}$ records span the AD 850 – AD 2016 period, showing generally st[illegible]values throughout the analyzed period, on which decadal to multi-decadal scale oscillations are superimposed. Both records display a remarkable similarity throughout the entire period~~,~~ and in our discussion we have used only $\delta^{18}O$.

Observations on the dynamics of cave ice during the past 18 years have shown that it starts to grow in early autumn by the freezing of water accumulated during sur[illegible]mer As the ceiling of the cave is opened to the exterior, precipitation directly reaches the site of ice formation, so that the stable isotope composition of precipitation is not modified in the epikarst above the cave ~~(Moldovan et al., 2012; Ersek et al., 2018),~~ thus preserving the original $\delta^{18}O$ ~~(~~and $\delta^{2}H$~~)~~ values of summer (June-July-August, JJA) precipitation. Further, $\delta^{18}O$ and $\delta^{2}H$ values in the FV ice core from the past 20 years are similar to values

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registered in the summer (JJA) precipitation at Ghețar (Fig. 3b) further supporting our inference that stable isotope values in cave ice preserve the summer climatic signal. However, while freezing processes in caves could alter the original $\delta^{18}O$ (and $\delta^{2}H$) values in cave ice, ~~Perşoiu et al. (2011b) have shown,~~ several studies have shown (e.g., in ~~form t~~the nearby Scărișoara Ice Cave (~~,~~ Perşoiu et al. (2011b)) that the original climatic signal embedded in the stable isotope composition of cave ice is preserved and can be used as a proxy for external climate variability.

Overall, our observations of cave ice genesis and dynamics and stable isotope monitoring data clearly indicate that summer air temperatures are registered and preserved in the ice block in FV Cave. In order to test the long-term preservation of these connections, we have analyzed the links between the FV $\delta^{18}O_{ice}$ record and instrumental data from three nearby meteorological stations over the AD 1851 – AD 2016 period. On multidecadal time scales, summer air temperature changes in the region are controlled mainly by the dynamics of the Atlantic Multidecadal Oscillation (Ionita et al., 2012). Fig. 4. shows the JJA air temperature at Baia Mare (BM), Sibiu (SB) and Timișoara (TM) stations, the AMO index and FV $\delta^{18}O_{ice}$. The instrumental temperature data indicates large multidecadal variability, with a cold period between AD 1890 and AD 1920, followed by a warm period between AD 1921 and AD 1960, a slightly colder period between AD 1960 and AD 2000, and enhanced warming over the last two decades, all following the AMO variability. The $\delta^{18}O_{ice}$ values show a similar temporal evolution, the slight offsets between the observational data and $\delta^{18}O$ being likely due to the dating uncertainty (20 – 35 years). ~~Since the variability of AMO index is strongly associated with the prevailing sea surface temperature (SST) anomalies over the North Atlantic Ocean basin (Sutton and Dong, 2012)~~Further, we have computed the correlation map between the summer mean air temperature at SB station (with the longest instrumental record) and the summer SST as indicator of AMO variability (Sutton and Dong, 2012). To remove short-term variability and retain only th~~e~~e multidecadal signal in our data, prior to the correlation analysis, both the temperature time series and the SST data were smoothed with a 21-year running mean filter. Figure 5 clearly shows that positive (negative) temperature anomalies over the analyzed region are associated with positive (negative) SST anomalies over the North Atlantic Ocean, resembling the SST anomalies associated with the positive (negative) phase of AMO (Mesta-Nuñez and Enfield 1999, Latif et al. 2004; Knight et al. 2005). These results are also in agreement with the results of Della-Marta et al. (2007), showing that extreme high temperatures over Europe are triggered, at least partially, by the phase of AMO. A recent study of $\delta^{18}O$ variability in oak tree rings in NW Romania (~50 km NW from our site) also indicates the influence of the AMO on summer temperatures and drought conditions (Nagavciuc et al., 2019a). A potential physical mechanisms for the multidecadal variability of $\delta^{18}O$ in our ice cave can be as follows: prolonged periods of positive temperature anomalies throughout the summer months ~~, due~~related to prolonged warm SST in the North Atlantic Ocean, lead to high ~~values of~~ $\delta^{18}O$ values ~~at our site location~~in the FV ice core via enhanced ice melting, while prolonged cold summers related~~, due~~ to a cold North Atlantic Ocean, lead ~~to more~~to low ~~negative~~ $\delta^{18}O$ values.

Combining all data above, it results that~~,~~ on time scales ranging from years to decades, prolonged periods of positive temperature anomalies throughout the summer months, linked to prolonged warm SSTs in the North Atlantic Ocean (and thus a positive AMO index), could be preserved by the $\delta^{18}O_{ice}$ in FV Ice Cave. We have compared the FV $\delta^{18}O_{ice}$ with tree ring width (TRW) reconstruction of JJA temperature anomalies (Popa and Kern, 2009). The highest similarities between the FV ice core and TRW records were found for the cold periods between AD 1000 – 1050, 1250 – 1300, 1420 – 1680, 1750 – 1850 and 1960 – 1980 and the warm periods during AD 1080 – 1200, 1850 – 1960. In contrast, some differences have been identified during the period AD 1640 – 1740, when the TRW record indicated above-average summer temperatures while the $\delta^{18}O$ record shows low values which suggest below – average summer temperatures (Fig. 7). Given the very different nature of the two archives (trees versus cave ice), of the proxies (TRW and $\delta^{18}O$) and of the chronologies (annual tree ring counting vs. ^{14}C dating), the two records agree remarkably well, further supporting the hypothesis that $\delta^{18}O$ ~~(~~and $\delta^{2}H$~~)~~ values in FV ice core is registering both summer air temperature variability during the past ca. 1000 years in East-Central Europe, as well as, on a broader spatial scale, the variability of the AMO.

Similar to the AD 1850-2016 interval described above, the stable isotope record closely mirrors the AMO variability over the entire studied interval (Fig. 6), suggesting a possible link between summer temperatures in Eastern Europe and solar influence. The relationship between the FV $\delta^{18}O_{ice}$ and AMO records is strongest between ~AD 1750 and AD 2016 and between AD 1125 and AD 1525, with decadal-scale variability in the two records being synchronous within the dating uncertainty (i.e., less than 30 years lag).

The apparent ~50 yrs lag of the FV $\delta^{18}O_{ice}$ record behind the AMO between AD 1600 and AD 1775 could have resulted from 1) high (> 50 years) uncertainty between AD 1525 and AD 1750, as well as before AD 1125 (Fig. 7a); 2) uncertainties in the reconstruction of AMO indexes before the instrumental record. Kilbourne et al. (2013) have shown, by comparing different proxy records of the AMO, that there is no consensus yet on the history of Atlantic multidecadal variability. Despite the similarities during the instrumental period, all the records they used in their study are quite different during the pre-instrumental era, most likely due to a lack of available well-dated, high-resolution marine proxy temperature records; 3) a less-straightforward link between solar forcing and the AMO (Knudsen et al., 2014) during the LIA. However, we do see the apparent breakdown of the correlation between summer temperatures and AMO only for a short period between AD 1600 and 1750~~, and also~~ as well as around AD 1050, periods when our chronology has the highest uncertainties. Further, the overall succession of high and low $\delta^{18}O$ values mimics the changes seen in the AMO reconstruction, so that the discrepancies could be the result of these uncertainties. If so, the record presented here suggest that solar-induced changes in the North Atlantic are transferred, likely *via* atmospheric processes, towards the wider Northern Hemisphere, resulting in hemispheric-wide climatic responses to perturbations in the North Atlantic

Several periods of excursions towards low $\delta^{18}O$ values (suggesting low summer temperatures) dot the past 1100 years (Fig. 7), the most notable one being around AD 870-930, AD ~~1030~~1045-1080, AD ~~1245~~1270-132~~5~~5, AD ~~1425~~1430-1475~~90~~, AD 152~~0~~5-1550, AD ~~1680~~1715-173~~2~~0, AD 1820-1865 and AD ~~1820-1850 and AD 1855-1925~~1880-1925. Significant maxima occurred between AD 850-875, AD ~~940~~1010-1030, AD ~~1100~~1350-139~~24~~0, AD 1485-1510,~~ and~~ AD ~~1630~~1625-1695 and AD 1950-1970~~70~~. All these minima and maxima, except for the one centered on AD 1840 coincide (Fig. 7) with the known solar minima and maxima of the past 1000 years (the Spörer Minimum between AD 1450 and AD 1550 is split in two in our record, by a brief interval of possibly high temperatures around AD 1500, similarly to the other records from Europe).

The FV $\delta^{18}O_{ice}$ record is in agreement with other summer temperature reconstructions (~~Moberg et al., 2005;~~e.g., Buntgen et al., 2011) at regional and hemispheric scale (Fig. 7). Further, regional summer temperature ~~reconstructions~~ (e.g., Popa and Kern, 2009~~; Seim et al., 2012; Drăgușin et al., 2014~~) and summer temperature-sensitive drought (Seim et al., 2012) reconstructions show warm peaks around AD 1320, 1420, 1560, 1780 and cooling around AD 1260, 1450 and 1820, similar with reconstructions and models at global level (Neukom et al., 2019) and the FV temperature reconstruction (this study). Contrary to the summer season temperature reconstructions, a late-autumn through early winter season temperature reconstructions from the nearby Scărișoara Ice Cave (Perșoiu et al., 2017) shows that the MWP was rather warm and also wet (Feurdean et al., 2011), while the LIA was cold, and likely drier and~~(but~~ wi~~o~~th ~~more erraticaly~~erratically ~~distruibuted~~distributed precipitation~~, Perșoiu and Perșoiu, 2019)~~. Together, these data suggest a complex picture of climate variability in the wider Carpathian region, with much of the yearly temperature ~~varaibility~~variability during the past 1000 years being ~~atributed~~attributed to the influence of winter conditions, summer temperatures being rather constant. On this long-term trend, brief "excursions" were likely the result of large-scale circulation influences, with solar variability induced changes being transferred locally by atmospheric processes.

5 Conclusions

The analysis of the oxygen and hydrogen stable isotope ratios along a ~5 m long ice core extracted from Focul Viu Ice Cave (~~NW~~ northwest Romania) provided an unprecedented view on the dynamics of summer air temperature and atmospheric circulation changes during the past 1000 years in the poorly investigated region of East-Central Europe. The data show~~s~~ little millennial-scale summer temperature variability since the onset of the Medieval Warm Period and through the Little Ice Age. Nevertheless, w~~W~~ell-expressed minima and maxima occurred synchronously with periods of low and high solar activity, possibly suggesting a causal mechanism. Similarly, decadal-scale summer temperature variability follows that of the Atlantic Multidecadal Oscillation, and we subsequently hypothesize that solar-induced changes in summer climatic conditions over the Northern Atlantic are transferred through atmospheric processes across the Northern Hemisphere. Similar records ~~from further east~~ are thus required to test this hypothesis. Contrary to summer temperatures, winter ones show a stronger contrast between the Medieval Warm Period and the Little Ice Age, thus suggesting that the later were likely an expression of winter climatic conditions.

Author contributions. CAB and AP designed the project, AP and CAB collected the ice core and CAB performed the stable isotope analyses. NP performed the radiocarbon analyses and constructed the depth-age model. MI analyzed the climate and large-scale circulation data. CBD and AP wrote the text, with input from MI and NP.

Competing interests. The authors declare that they have no conflict of interest.

Data availability. The Focul Viu $\delta^{18}O$ and $\delta^{2}H$, as well as the ^{14}C data and the modeled ages will be made available upon publication, both on the CP webpage and on the NOAA/World Data Service for Paleoclimatology webpage The meteorological data plotted in figure 4 was provided by the Romanian National Meteorological Administration, except for the AMO data (panel a) which was downloaded from https://climexp.knmi.nl/data/iamo_ersst_ts.dat. The paleoclimate data used to plot fig. 7, panels a, b, c, d~~, f~~ and ~~g~~ e was downloaded from the NOAA/World Data Service for Paleoclimatology webpage. ~~Data used in fig. 7e was provided by Virgil Drăgușin and is published in Drăgușin et al. (2014).~~

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References

Bădăluță, C.–A.**,** Persoiu, A., Ionita, M., Nagavciuc, V., and Bistricean, P. I.: Stable H and O isotope-based investigation of moisture sources and their role in river and groundwater recharge in the NE Carpathian Mountains, East-Central Europe, Isot. Environ. Healt. S., 55 (2), 161–178, https://doi.org/10.1080/10256016.2019.1588895, 2019.

Brad, T., Bădăluță C.-A., and Persoiu, A.: Ice caves in Romania, in: Ice caves, edited by: Perşoiu, A. and Lauritzen, S.-E., Elsevier, Amsterdam, Netherlands, 511–528, https://doi.org/10.1016/B978-0-12-811739-2.00025-5, 2018.

Bojar, A, Ottner, F, Bojar, H. P., Grigorescu, D., and Persoiu, A.: Stable isotope and mineralogical investigations on clays from the Late Cretaceous sequences, Haţeg Basin, Romania, Appl. Clay Sci., 45, 155–163, https://doi.org/10.1016/j.clay.2009.04.005, 2009.

Bronk Ramsey, C. and Lee, S.: Recent and Planned Developments of the Program OxCal, Radiocarbon, 55, 720–730, https://doi.org/10.1017/S0033822200057878, 2013.

Bronk Ramsey, C.: Bayesian analysis of radiocarbon dates, Radiocarbon, 51, 337–360, 2009.

Bronk Ramsey, C.: Deposition models for chronological records, Quaternary Sci. Rev., 27, 42–60, https://doi.org/10.1016/j.quascirev.2007.01.019, 2008.

Büntgen, U., Tegel, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J. O., Herzig, F., Heussner, K-U., Wanner, H., Luterbacher, J., and Esper, J.: 2500 Years of European Climate Variability and Human Susceptibility, Science, 331, 578–582, https://doi.org/10.1126/science.1197175, 2011.

Citterio, M., Turri, S., Perşoiu, A., Bini, A., and Maggi, V.: Radiocarbon ages from two ice caves in the Italian Alps and the Romanian Carpathians and their significance, In: Glacier Caves and Glacial Karst in High Mountains and Polar Regions, edited by: Mavlyudov, B. R., Institute of geography of the Russian Academy of Sciences, Moscow, Russia, 87–92, 2005.

Colucci, R. R., and Guglielmin, M.: Climate change and rapid ice melt: Suggestions from abrupt permafrost degradation and ice melting in an alpine ice cave, Progress in Physical Geography: Earth and Environment, 43, 561-573, 10.1177/0309133319846056, 2019.

Colucci, R. R., Fontana, D., Forte, E., Potleca, M., and Guglielmin, M.: Response of ice caves to weather extremes in the southeastern Alps, Europe, Geomorphology, 261, 1-11, http://dx.doi.org/10.1016/j.geomorph.2016.02.017, 2016.

Coumou, D., and Rahmstorf, S.: A decade of weather extremes, Nat. Clim. Change, 2, 491–496, https://doi.org/10.1038/nclimate1452, 2012.

Craig, H.: Isotopic variations in meteoric waters, Science, 133, 1702–1703, https://doi.org/10.1126/science.133.3465.1702, 1961.

D'Arrigo, R., Wilson, R., and Jacoby G.: On the long-term context for late twentieth century warming, J. Geophys. Res., 111, D03103, https://doi.org/10.1029/2005JD006352, 2006.

Dansgaard, W.: Stable isotope in precipitation, Tellus, 16, 436–438, https://doi.org/10.1111/j.2153-3490.1964.tb00181.x, 1964.

Della-Marta, P. M., Luterbacher, J., von Weissenfluh, H., Xoplaki, E., Brunet, M., and Wanner, H.: Summer heat waves over western Europe 1880–2003, their relationship to large scale forcings and predictability, Clim. Dynam., 29, 251–275, https://doi.org/10.1007/s00382-007-0233-1, 2007.

Dragusin, V., Balan, S., Blamart, D., Forray, F. L., Marin, C., Mirea, I., Nagavciuc, V., Persoiu, A., Tirla, L., Tudorache, A., and Vlaicu, M.: Transfer of environmental signals from surface to the underground at Ascunsă Cave, Romania, Hydrol. Earth Syst. Sci., 21, 5357–5373, https://doi.org/10.5194/hess-21-5357-2017, 2017.

~~Ersek, V., Onac, B. P., and Perşoiu, A.: Kinetic processes and stable isotopes in cave dripwaters as indicators of winter severity, Hydrol. Process., 32, 2856–2862, https://doi.org/10.1002/hyp.13231, 2018.~~

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

Feurdean, A., Galka, M, Kuske, E., Tanţău, I., Lamentowicz, M., Florescu, G., Liakka, J., Hutchinson, S. M., Mulch, A., and Hickler, T.: Last Millennium hydro-climate variability in Central Eastern Europe (Northern Carpathians, Romania), Holocene, 25, 1179–1192, https://doi.org/10.1177/0959683615580197, 2015.

Fórizs, I., Kern, Z., Szántó, Zs., Nagy, B., Palcsu, L., Molnár, M.: Environmental isotopes study on perennial ice in the Focul Viu Ice Cave, Bihor Mountains, Romania. Theor. App. Karst.17, 61–69, 2004.

Haustein, K., Allen, M. R., Forster, P. M., Otto, F. E. L., Mitchell, D. M., Matthews, H. D., and Frame, D. J.: A real-time Global Warming Index, Sci. Rep., 7: 15417, https://doi.org/10.1038/s41598-017-14828-5, 2017.

Holmlund, P., Onac, B. P., Hansson, M., Holmgren, K., Morth, M., Nyman, M., and Persoiu, A.: Assessing the palaeoclimate potential of cave glaciers: the example of the Scărişoara Ice Cave (Romania), Geogr. Ann. A, 87A, 193–201, https://doi.org/10.1111/j.0435-3676.2005.00252.x, 2005.

Hua, Q., Barbetti, M., and Rakowski, A. Z.: Atmospheric Radiocarbon for the Period 1950–2010, Radiocarbon, 55, 2059–2072, https://doi.org/10.2458/azu_js_rc.v55i2.1, 2013.

Huang, B., Angel, W., Boyer, T., Cheng, L., Chepurin, G., Freeman, E., Liu, C., and Zhang, H.-M.: Evaluating SST analyses with independent ocean profile observations, J. Climate, 31, 5015–5030, https://doi.org/10.1175/JCLI-D-17-0824.1, 2018.

IPCC: Global warming of 1.5°C. An IPCC Special Report. Geneva, Switzerland, https://doi.org/10.1017/CBO9781107415324, 2018.

Ionita, M., Rimbu, N., Chelcea, S., and Patrut, S.: Multidecadal variability of summer temperature over Romania and its relation with Atlantic Multidecadal Oscillation, Theor. Appl. Climatol., 113, 305–315, https://doi.org/10.1007/s00704-012-0786-8, 2012.

Jones, P. D., Osborn, T. J., and Briffa, K. R.: The evolution of climate over the last millennium, Science, 292(5517), 662-667, https://doi.org/10.1126/science.1059126, 2001.

Jones, P. D., and Mann, M. E.: Climate over the past millennia, Rev. Geophys., 42, RG2002, https://doi.org/10.1029/2003RG000143, 2004.

Jones, P. D., Briffa, K. R., Osborn, T. J., Lough, J. M., van Ommen, T. D., Vinther, B. M., Luterbacher, J., Wahl, E. R., Zwiers, F. W., Mann, M. E., Schmidt, G. A., Ammann, C. M., Buckley, B. M., Cobb, K. M., Esper, J., Goosse, H., Graham, N., Jansen, E., Kiefer, T., Kull, C., Küttel, M., Mosley-Thompson, E., Overpeck, J. T., Riedwyl, N., Schulz, M., Tudhope, A. W., Villalba, R., Wanner, H., Wolff, E., and Xoplaki, E.: High-resolution palaeoclimatology of the last millennium: A review of current status and future prospects, The Holocene, 19, 3–49, https://doi.org/10.1177/0959683608098952, 2009.

Kern, Z., and Persoiu, A.: Cave ice - the imminent loss of untapped mid-latitude cryospheric palaeoenvironmental archives, Quaternary Sci. Rev., 67, 1-7, https://doi.org/10.1016/j.quascirev.2013.01.008, 2013.

Kern, Z., Fórizs, I., Nagy, B., Kázmér, M., Gál, A., Szánto, Z., Palcsu, L., and Molnár, M.: Late Holocene environmental changes recorded at Gheţarul de la Focul Viu, Bihor Mountains, Romania, Theor. App. Karst., 17, 51–60, 2004.

Kern, Z., Molnár, M., Svingor, É., Persoiu, A., and Nagy, B.: High-resolution, well-preserved tritium record in the ice of Bortig Ice Cave, Bihor Mountains, Romania, The Holocene, 19, 729-736, https://doi.org/10.1177/0959683609105296, 2009.

Kern, Z., Bočić, N., and Sipos, G.: Radiocarbon-Dated Vegetal Remains from the Cave Ice Deposits of Velebit Mountain, Croatia, Radiocarbon, 60, 1391-1402, https://doi.org/10.1017/RDC.2018.108, 2018.

Kilbourne, K. H., Alexander, M. A., and Nye, J. A.: A low latitude paleoclimate perspective on Atlantic multidecadal variability, J. Marine Syst., 133, 4–13, https://doi.org/10.1016/j.jmarsys.2013.09.004, 2013.

Knight, J. R., Allan, R. J., Folland, C. K., Vellinga, M., and Mann, M.E.: A signature of persistent natural thermohaline circulation cycles in observed climate, Geophys. Res. Lett., 32, L20708, https://doi.org/10.1029/2005GL024233, 2005.

Knudsen, M. F., Jacobsen B. H., Seidenkrantz, M.-S., and Olsen, J.: Evidence for external forcing of the Atlantic Multidecadal Oscillation since termination of the Little Ice Age, Nat. Commun., 5: 3323, https://doi.org/10.1038/ncomms4323, 2014.

Koci, B. R., and Kuivinen, K. C.: The PICO lightweight coring auger, J. Glaciol., 30, 244–245, https://doi.org/10.3189/S0022143000006018, 1984.

Latif, M., Botset, E. R. M., Esch, M., Haak, H., Hagemann, S., Jungclaus, J., Legutke, S., Marsland, S., and Mikolajewicz, U.: Reconstructing, monitoring and predicting multidecadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature, J. Climate, 17, 1605–1614, https://doi.org/10.1175/1520-0442(2004)017<1605:RMAPMC>2.0.CO;2, 2004.

Leunda, M., González-Sampériz, P., Gil-Romera, G., Bartolomé, M., Belmonte-Ribas, Á., Gómez-García, D., Kaltenrieder, P., Rubiales, J. M., Schwörer, C., Tinner, W., Morales-Molino, C., and Sancho, C.: Ice cave reveals environmental forcing of long-term Pyrenean tree line dynamics, J. Ecol., 107, 814-828, https://doi.org/10.1111/1365-2745.13077, 2019.

Ljungqvist, F. C., Seim, A., Krusic, P. J., González-Rouco, J. F., Werner, J. P., Cook, E. R., Zorita, E., Luterbacher, J., Xoplaki, E., Destouni, G., García-Bustamante, E., Aguilar, C. A. M., Seftigen, K., Wang, J., Gagen, M. H., Esper, J., Solomina, O., Fleitmann, D., and Büntgen, U.: European warm-season temperature and hydroclimate since 850 CE, Environ. Res. Lett., 14, 084015, https://doi.org/10.1088/1748-9326/ab2c7e, 2019.

Maggi, V., Turri, S., Bini, A., and Udisti, R.: 2500 Years of history in Focul Viu Ice Cave, Romania, In: Proceedings of the 3rd International Workshop on Ice Caves, edited by: Kadebskaya, O., Mavlyudov, B., and Patunin, M., Kungur Ice Cave, Russia, 11–15, 2008.

Mann, M. E., Zhang, Z., Rutherford, S., Bradley, R., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256–1260, https://doi.org/10.1126/science.117730, 2009.

Mavlyudov, B. R.: Ice genesis and types of ice caves, in: Ice caves, edited by: Perşoiu, A. and Lauritzen, S. E., 34-68, https://doi.org/10.1016/B978-0-12-811739-2.00032-2, 2018.

Mesta-Nuñez, A. M., and Enfield, D. B.: Rotated global modes of non-ENSO sea surface temperature variability, J. Climate, 12, 2734–2746, https://doi.org/10.1175/1520-0442(1999)012<2734:RGMONE>2.0.CO;2, 1999.

Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko, N. M. and Karlén, W.: Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data, Nature, 433, 613-617, https://doi.org/10.1038/nature03265, 2005.

~~Moldovan, O., Meleg, I., and Persoiu, A.: Habitat fragmentation and its effects on groundwater populations, Ecohydrology, 5, 445–452, https://doi.org/10.1002/eco.237, 2012.~~

Nagavciuc V., Bădăluță C.-A., Ionita M.: Tracing the Relationship between Precipitation and River Water in the Northern Carpathians Base on the Evaluation of Water Isotope Data, Geosciences, *9*, 198; https://doi.org/10.3390/geosciences9050198, 2019.

Nagavciuc, V., Ionita, M., Persoiu, A., Popa, I., Loader, N. J., and McCarroll, D.: Stable oxygen isotopes in Romanian oak tree rings record summer droughts and associated large-scale circulation patterns over Europe, Clim. Dynam., 52, 6557–6568, https://doi.org/10.1007/s00382-018-4530-7, 2019a.

Nemec, M., Wacker, L., and Gäggeler, H. W.: Optimization of the Graphitization Process at AGE-1, Radiocarbon, 52, 1380–1393, 2010.

Neukom, R., Steiger, N., Gómez-Navarro, J.J., Wang, J. and Werner, J. P.: No evidence for globally coherent warm and cold periods over the preindustrial Common Era, Nature, 571, 550–554, https://doi.org/10.1038/s41586-019-1401-2, 2019.

Orghidan, T., Negrea, Ş., Racoviţă, G., and Lascu, C.: Peşteri din România: ghid turistic. Ed. Sport-Turism, Bucureşti, 1984.

O'Reilly, C. H., Woollings, T., and Zanna, L.: The Dynamical Influence of the Atlantic Multidecadal Oscillation on Continental Climate, J. Climate, 30, 7213–7230, https://doi.org/10.1175/JCLI-D-16-0345.1, 2017.

PAGES 2K Consortium: Consistent multidecadal variability in global temperature reconstructions and simulations over the Common Era, Nat. Geosci., 12, 643–649, https://doi.org/10.1038/s41561-019-0400-0, 2019.

Persoiu, A.: Climate evolution during the Late Glacial and the Holocene. In: Landform dynamics and evolution in Romania, edited by: Rădoane, M., and Vespremeanu-Stroe, A., Springer, Berlin, Heidelberg, Germany, 57–66. https://doi.org/10.1007/978-3-319-32589-7_3, 2017.

Persoiu, A., and Pazdur, A: Ice genesis and its long-term dynamics in Scărişoara Ice Cave, Romania, The Cryosphere, 5, 45–53, https://doi.org/0.5194/tc-5-45-2011, 2011.

Persoiu, A., and Onac, B. P.: Ice caves in Romania, In: Cave and Karst Systems of Romania, edited by: Ponta, G. M. L., and Onac, B. P., Springer, Berlin, Heidelberg, Germany, 455–465, https://doi.org/10.1007/978-3-319-90747-5_52, 2019.

Persoiu, A., Onac, B. P., and Perşoiu, I.: The interplay between air temperature and ice dynamics in Scărişoara Ice Cave, Romania. Acta Carsologica, 40, 445–456, https://doi.org/10.3986/ac.v40i3.4, 2011a.

Persoiu, A., Onac, B. P., Wynn, J. G., Bojar, A.-V., and Holmgren, K.: Stable isotope behavior during cave ice formation by water freezing in Scărişoara Ice Cave, Romania, J. Geophys. Res., 116, D02111, https://doi.org/10.1029/2010JD014477, 2011b.

Persoiu, A, Onac, B. P., Wynn, J. G., Blaauw, M., Ionita, M., and Hansson, M.: Holocene winter climate variability in Central and Eastern Europe, Sci. Rep., 7: 1196, https://doi.org/10.1038/s41598-017-01397-w, 2017.

Persoiu, A., Ionita, M., and Weiss H.: Atmospheric blocking induced by the strengthened Siberian High led to drying in the Middle East during the 4.2 ka event –a hypothesis, Clim. Past, 15, 781–793, https://doi.org/10.5194/cp-2018-161, 2019.

Persoiu, A., Buzjak, N., Onaca, A., Pennos, C., Sotiriadis, Y., Ionita, M., Zachariadis, S., Kosutnik, J., Hegyi, A., and Butorac, V.: Accelerated loss of surface and cave ice in SE Europe related to heavy summer rains, The Cryosphere, under review.

Piotrowska, N.: Status report of AMS sample preparation laboratory at GADAM Centre, Gliwice, Poland, Nuclear Instruments and Methods in Physics Research Section B, 294, 176–181, 2013.

Popa, I., and Kern, Z.: Long-Term Summer Temperature Reconstruction Inferred from Tree-ring Records from the Eastern Carpathians, Clim. Dyn., 32, 1107–1117, https://doi.org/10.1007/s00382-008-0439-x, 2009.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatte, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M., and van der Plicht J.: IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0-50,000 Years cal BP, Radiocarbon, 55, 1869–1887, https://doi.org/10.2458/azu_js_rc.55.16947, 2013.

Sancho, C., Belmonte, Á., Bartolomé, M., Moreno, A., Leunda, M., and López-Martínez, J.: Middle-to-late Holocene palaeoenvironmental reconstruction from the A294 ice-cave record (Central Pyrenees, northern Spain), Earth Planet. Sci. Lett., 484, 135-144, https://doi.org/10.1016/j.epsl.2017.12.027, 2018.

Seim, A., Büntgen, U., Fonti, P., Haska, H., Herzig, F., Tegel, W., Trouet, V., and Treydte, K.: Climate sensitivity of a millennium-long pine chronology from Albania, Clim. Res., 51, 217–228, https://doi.org/10.3354/cr01076, 2012.

Steinhilber, F., Beer, J., and Fröhlich, C.: Total solar irradiance during the Holocene, Geophys. Res. Lett., 36, L19704, https://doi.org/10.1029/2009GL040142, 2009.

Sutton, R. T., and Dong, B.: Atlantic Ocean influence on a shift in European climate in the 1990s, Nat. Geosci., 5, 788–792, https://doi.org/10.1038/ngeo1595, 2012.

Wacker, L., Nemec, M., and Bourquin, J.: A revolutionary graphitisation system: Fully automated, compact and simple, Nucl. Instrum. Meth. B, 268 (7-8), 931–934, 2010.

Wang, J., Yang, B., Ljungqvist, F. C., Luterbacher, J., Osborn, T.J., Briffa, K. R., and Zorita, E.: Internal and external forcing of multidecadal Atlantic climate variability over the past 1,200 years, Nat. Geosci., 10, 512–517, https://doi.org/10.1038/ngeo2962, 2017.

Zoppi, U., Crye, J., Song, Q., and Arjomand A.: Performance evaluation of the new AMS system at Accium BioSciences, Radiocarbon, 49, 173–182, 2007.

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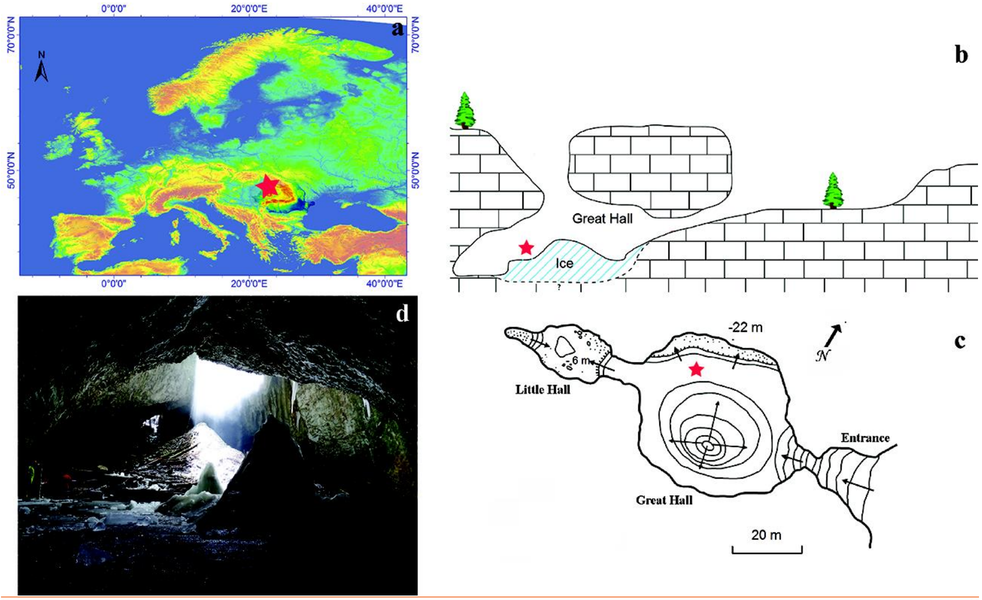


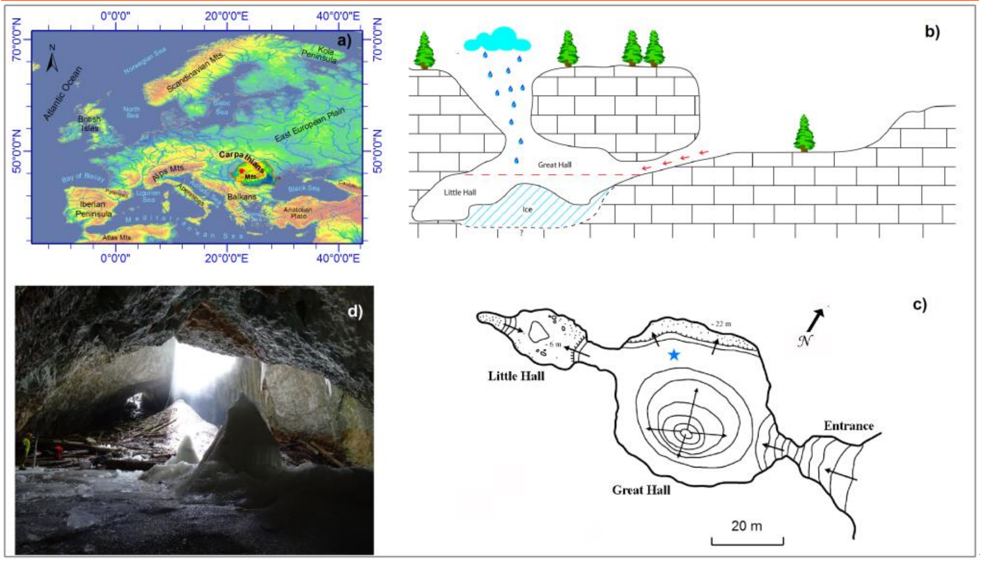
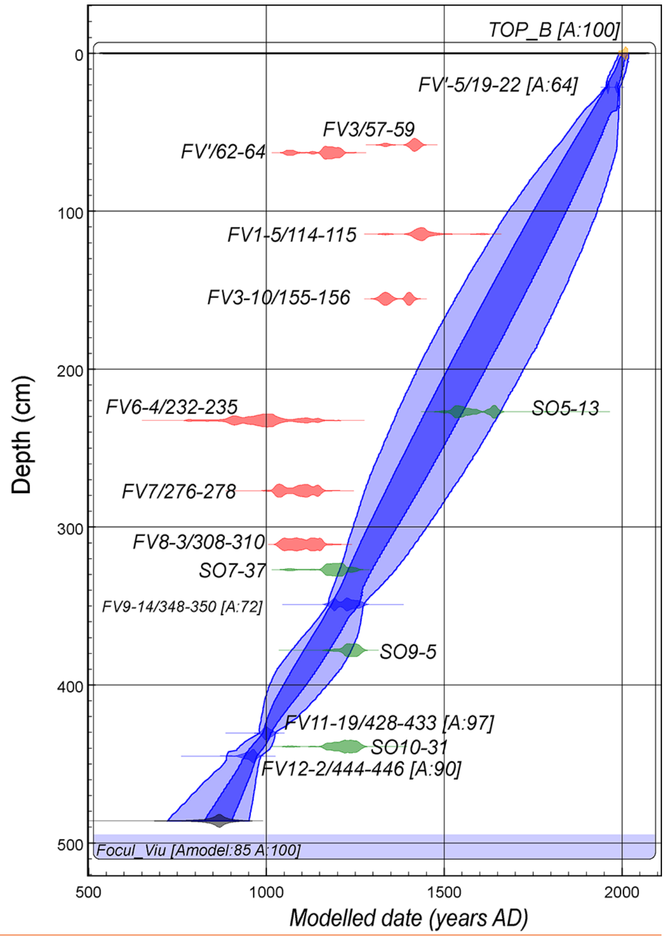


Figure 1. Location of the Focul Viu Ice Cave (red ~~point~~star) in Europe (a)~~, and transversal~~ cross section (b) and ~~longitudinal~~ map (c) ~~cross section through the cave~~of the cave (red ~~. The blue~~ star ~~(c)~~ indicates the drilling ~~point~~ site ~~in the Great Hall (d) of the cave.~~) and (d) general view of the Great Hall (person in yellow on the left is standing at the drilling site).


TOP_B [A:100]
FV'-5/19-22 [A:64]
FV3/57-59
FV'/62-64
FV1-5/114-115
FV3-10/155-156
FV6-4/232-235
SO5-13
FV7/276-278
FV8-3/308-310
SO7-37
FV9-14/348-350 [A:72]
SO9-5
FV11-19/428-433 [A:97]
SO10-31
FV12-2/444-446 [A:90]
Focul_Viu [Amodel:85 A:100]
Depth (cm)
0
100
200
300
400
500
Modelled date (years AD)
500
1000
1500
2000

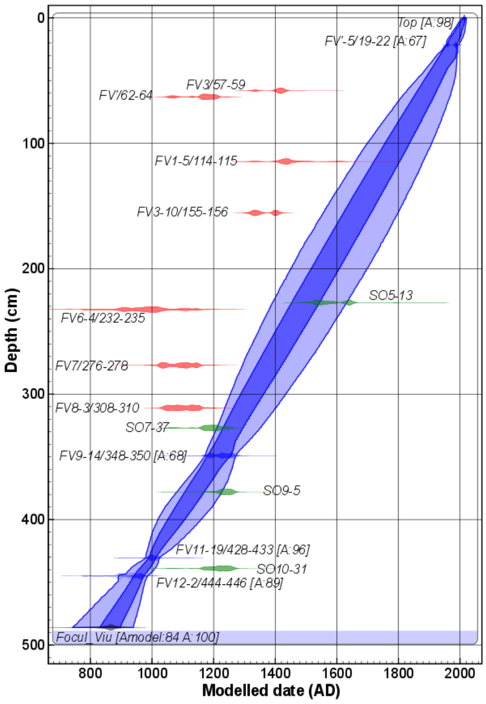
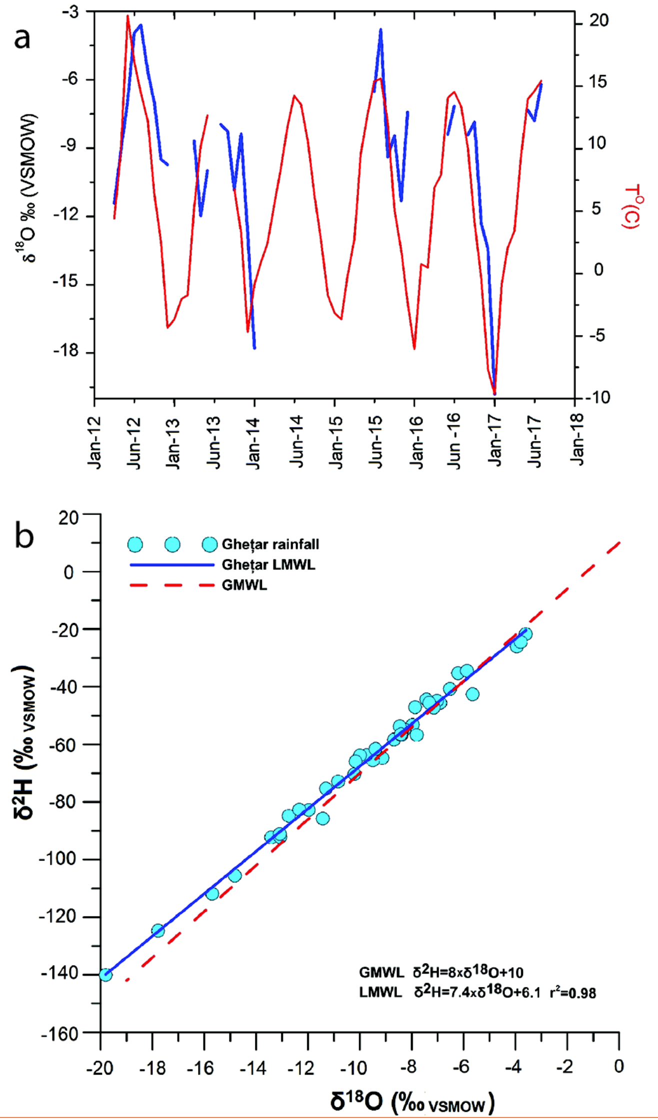
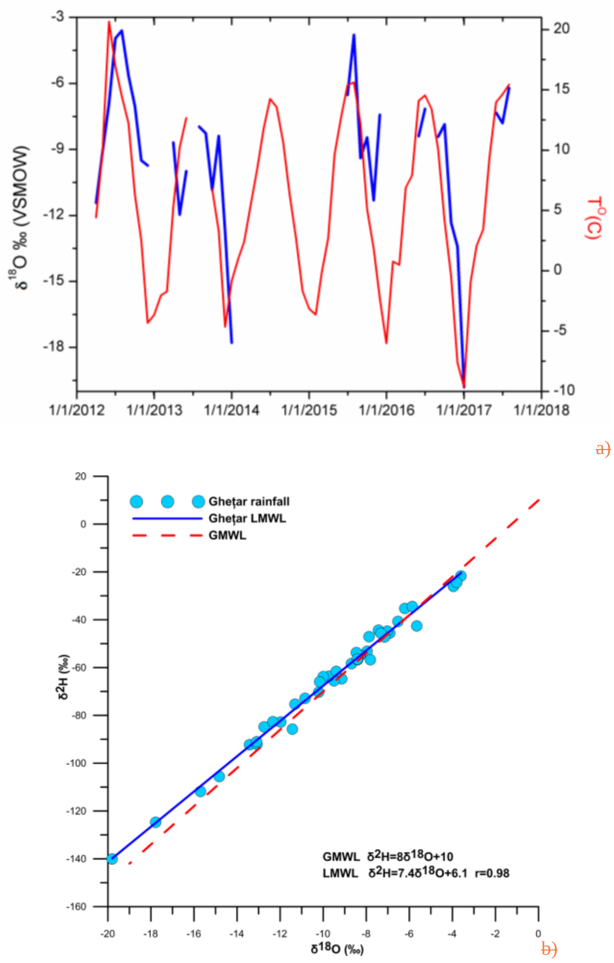


Figure 2. ~~Depth age~~Age-depth model of the Focul Viu ice core. The calibrated age range of ~~dated~~ samples used in the model is indicated in blue and ~~the dates~~for those rejected, in red. Samples in green are from the ice core drilled in 2004 (~~Green - dates from~~ Maggi et al., ~~(~~2008).


a
-3
-6
-9
-12
-15
-18
δ18O ‰ (VSMOW)
20
15
10
5
0
-5
-10
T°(C)
Jan-12
Jun-12
Jan-13
Jun-13
Jan-14
Jun-14
Jan-15
Jun-15
Jan-16
Jun -16
Jan-17
Jun-17
Jan-18
b
Ghețar rainfall
Ghețar LMWL
GMWL
GMWL δ2H=8xδ18O+10
LMWL δ2H=7.4xδ18O+6.1 r²=0.98
20
0
-20
-40
-60
-80
-100
-120
-140
-160
δ2H (‰ VSMOW)
-20
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
δ18O (‰ VSMOW)



~~a)~~

~~b)~~

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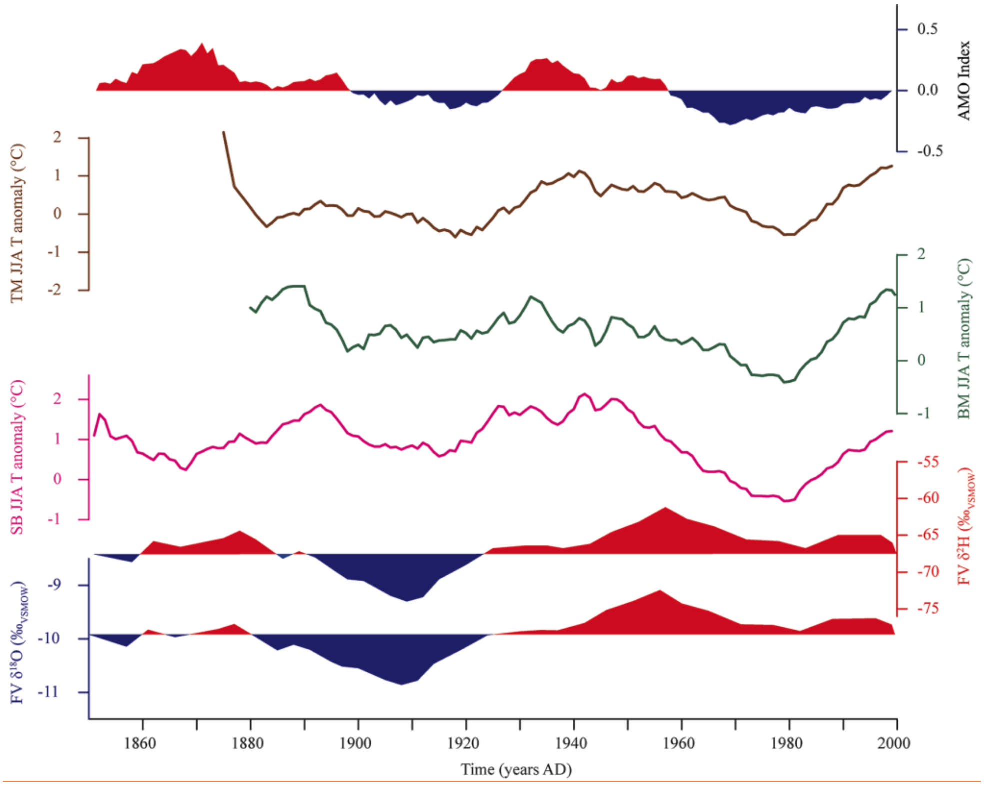
Figure 3. a) Temporal variability of δ^{18}O and δ^{2}H in precipitation and air temperature at Gheţar (10 km south of Focul Viu Ice Cave and at the same altitude), b)~~and the~~ Local Meteoric Water Line ~~for~~ of precipitation the same station, plotted against the Global Meteoric Water Line ~~.~~


0.5
0.0
-0.5
AMO Index
2
1
0
-1
-2
TM JJA T anomaly (°C)
2
1
0
-1
BM JJA T anomaly (°C)
2
1
0
-1
SB JJA T anomaly (°C)
-55
-60
-65
-70
-75
FV δ²H (‰VSMOW)
-9
-10
-11
FV δ¹⁸O (‰VSMOW)
1860
1880
1900
1920
1940
1960
1980
2000
Time (years AD)

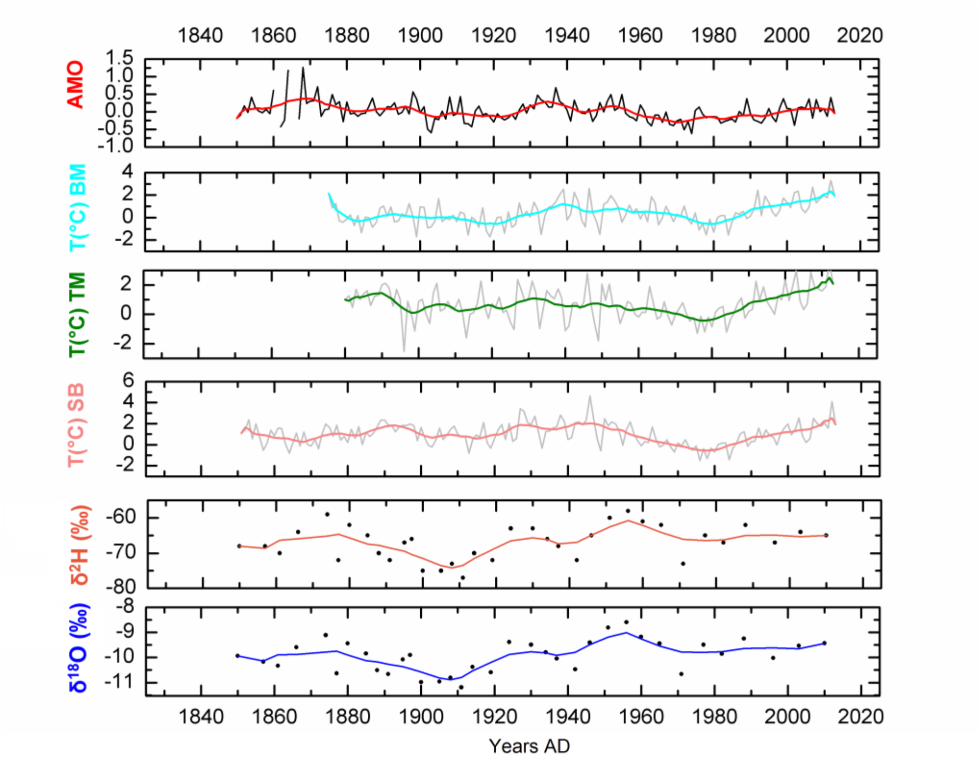
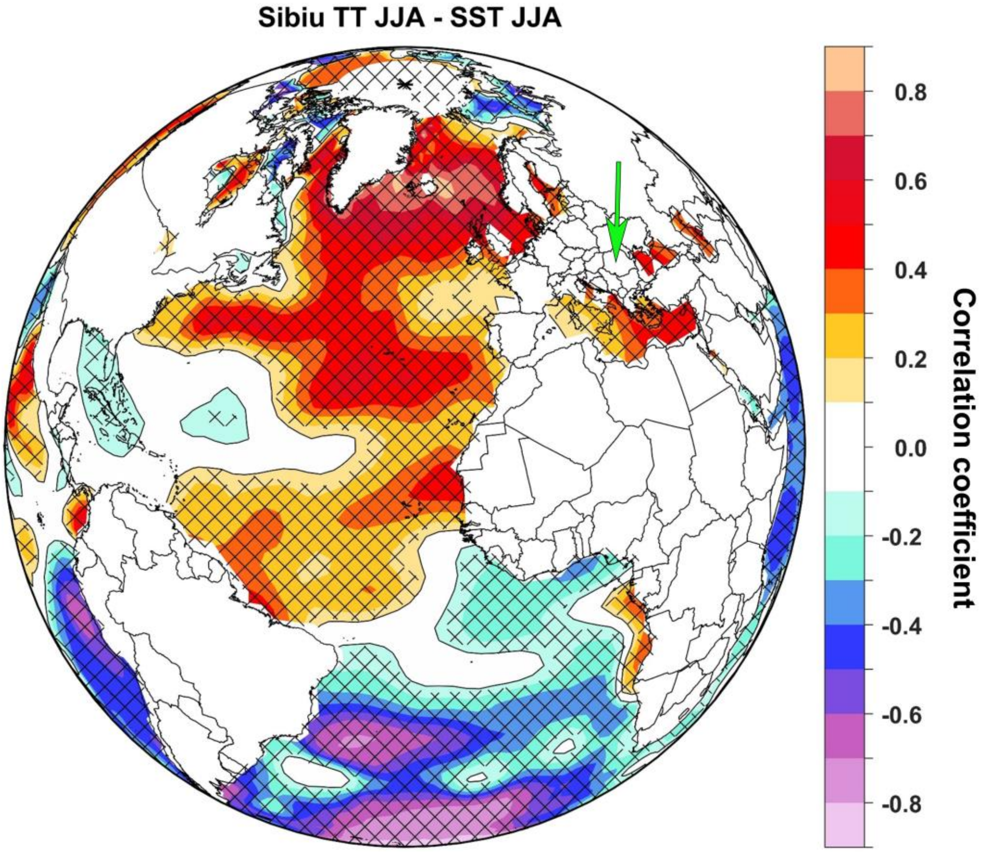


Figure 4. Temporal variability of the Atlantic Multidecadal Oscillation instrumental index, air temperature (anomalies with respect to the 1961-1990 period) recorded at Baia Mare (BM), Timișoara (TM) and Sibiu (SB) weather stations and FV δ^{18}O and δ^{2}H (‰) during the instrumental period. ~~The thick lines represent 5 years moving averages for the δ^{18}O and δ^{2}H record, and 11 years for the other records.~~The positive (red) and negative (blue) anomalies are shown against the 1850-2000 averages for the FV δ values


Sibiu TT JJA - SST JJA
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
Correlation coefficient

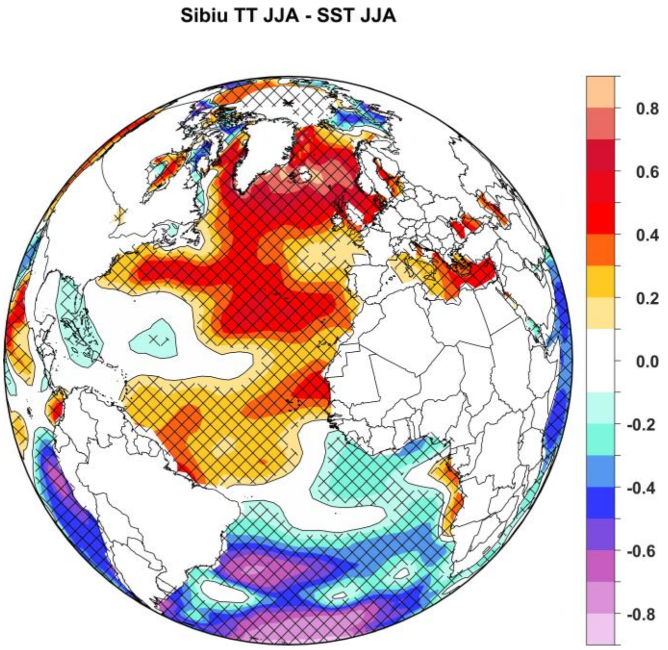
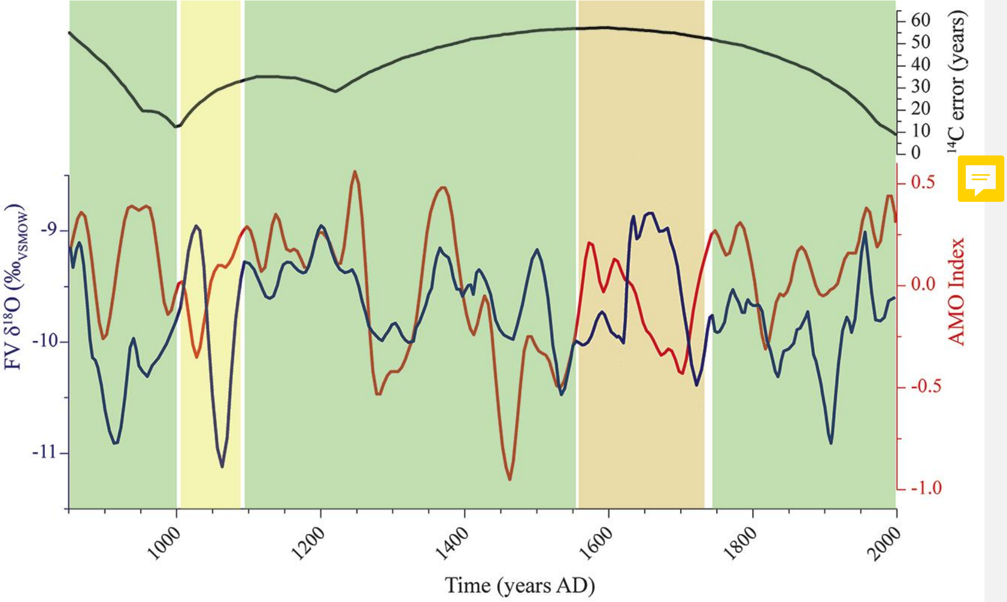


Figure 5. Spatial correlation map between Sea Surface Temperature (SST) and ~~Sibiu~~ average ~~Tmean in~~ summer (JJA June – July- August) air temperature at Sibiu (60 km south of Focul Viu Ice Cave, indicated by the green arrow) over the 1850-2011 period.~~.~~

~~Analyzed period: 1850 - 2011~~



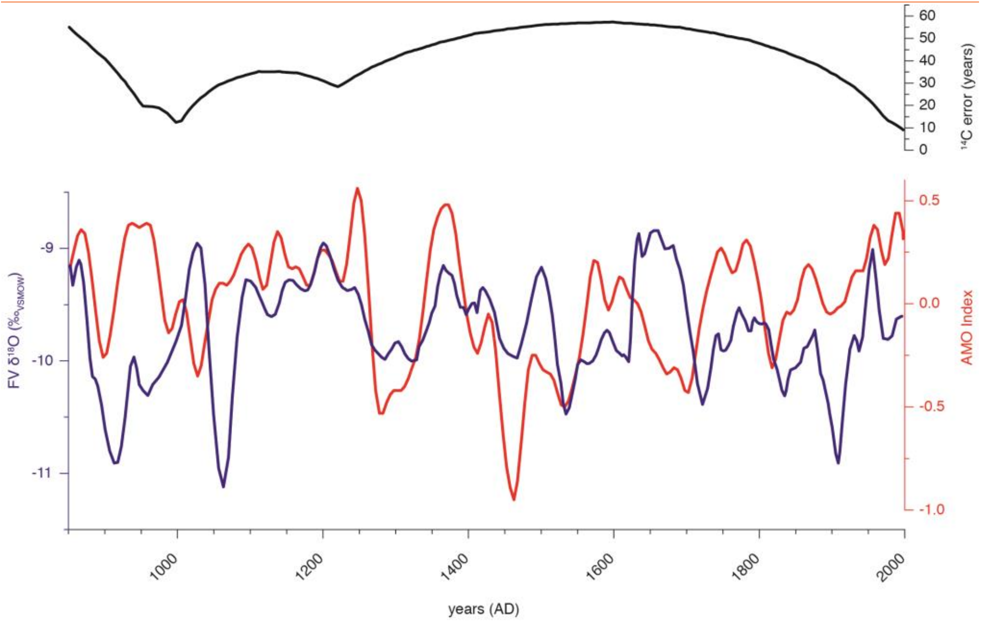
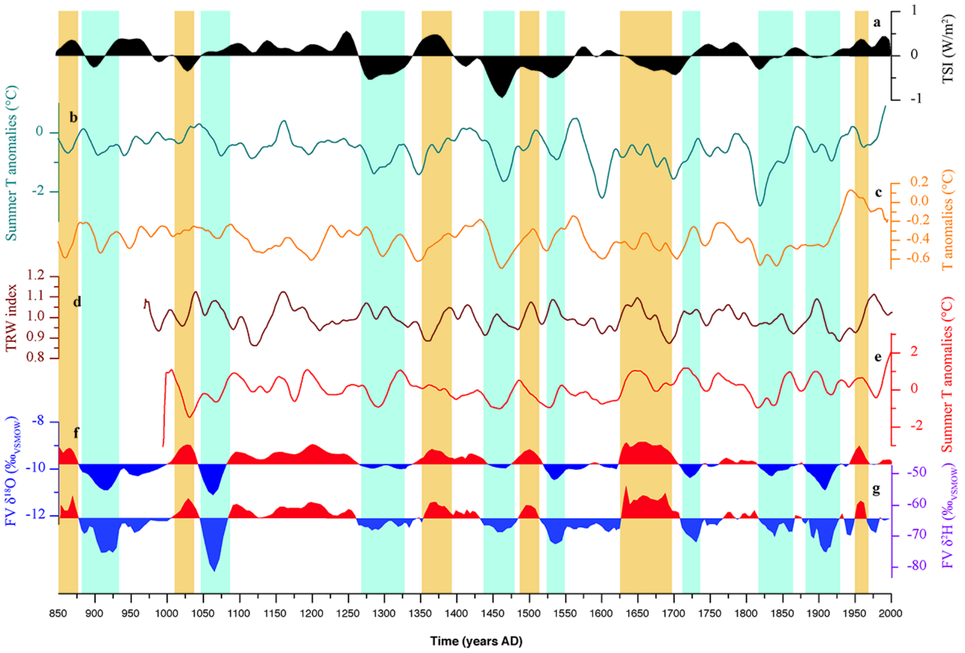


Figure 6. Temporal variability of the FV δ^{18}O (blue), the reconstructed AMO index (Wang et al., 2017) and the ^{14}C measurement uncertainty between AD 850 and 2000. Shading indicates the offset (in years) between the FV δ^{18}O and AMO index values: green – less than 20 years, yellow – between 20 and 50 years, orange – above 50 years.



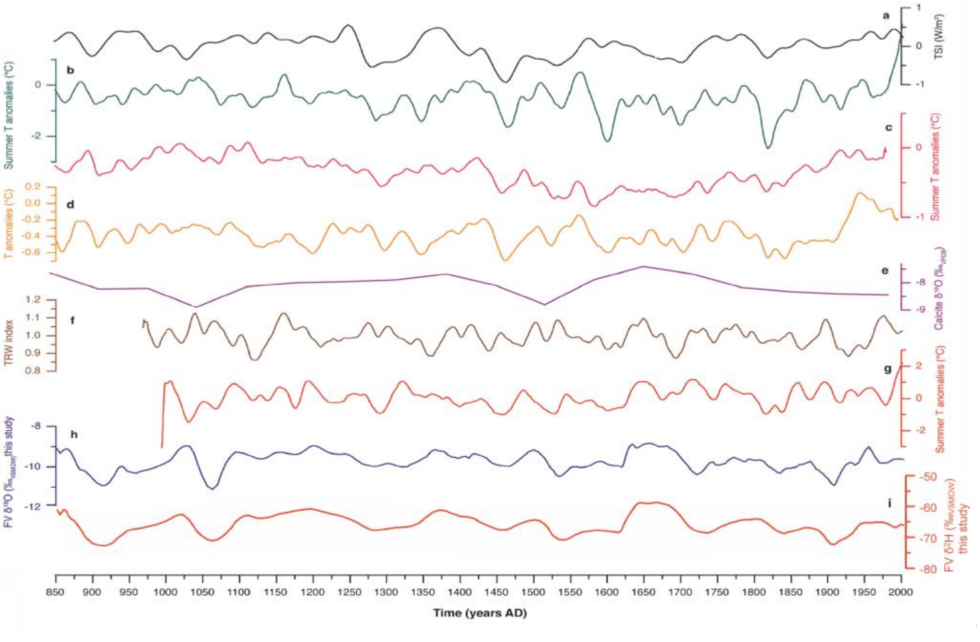


Figure 7. Summer climatic conditions recorded by δ^{18}O ~~(~~and δ^{2}H from FV ice core (~~,~~ panels ~~i~~f and ~~) from FV ice core (panel~~ g, ~~h,~~ bottom) and comparison with proxy indicator from the ~~Nordic~~ Northern Hemisphere: a) Total Solar Radiation (Steinhilber et al., 2009), b) Central Europe summer temperature anomalies (against the 1901-2000 mean, Buntgen et al., 2011); c) ~~Northern Hemisphere air temperature anomalies (against the 1961-1990 mean, Moberg et al. (2005); d)~~ Northern

Hemisphere air temperature anomalies (against the 1961-1990 mean, D’Arrigo et al., 2006), ~~e) Speleothem δ^{18}O from SW Romania (Drăgușin et al., 2014); f~~d) Tree Ring width index from Albania, SE Europe (Seim et al., 2012), ~~g~~e) Summer temperature anomalies in Romania (against the 1961-1990 mean, Popa and Kern, 2009).

Table 1. Radiocarbon data from the Focul Viu Ice Cave. Agreement indices for individual samples based on *P_Sequence* algorithm (Bronk Ramsey, 2008) are provided for accepted dates. Modeled ages for all dated depths are given as mean and sigma values, rounded to the nearest 5.

~~**Tabel 1.** Radiocarbon data from the Focul Viu Ice Cave~~

~~**No**~~	~~**Lab code GdA-**~~	~~**Sample name**~~	~~**Depth (cm)**~~	~~**Material**~~	~~**Sample mass (mgC)**~~	~~**^{14}C age (BP)**~~	~~**Status**~~	~~**Calibrated age range unmodelled (AD)**~~	~~**Modelled age mean age (AD)**~~
~~1~~	~~4889~~	~~FV'-5/19-22~~	~~21.5~~	~~needles and leaves, small fragments~~	~~0.86~~	~~-1410±25~~	~~accepted~~	~~1957-1992~~	~~1975±13~~
~~2~~	~~5084~~	~~FV3/57-59~~	~~58~~	~~leaf fragments~~	~~0.54~~	~~525±30~~	~~rejected~~	~~1322 – 1442~~	~~1891±36~~
~~3~~	~~4890~~	~~FV'/62-64~~	~~63~~	~~large wood fragment~~	~~1.00~~	~~875±25~~	~~rejected~~	~~1046 – 1223~~	~~1880±40~~
~~4~~	~~5085~~	~~FV15/114-115~~	~~114.5~~	~~needle fragment, small~~	~~0.25~~	~~470±50~~	~~rejected~~	~~1320-1619~~	~~1761±51~~
~~5~~	~~4891~~	~~FV3-10/155-156~~	~~155.5~~	~~small wood fragment~~	~~0.61~~	~~570±25~~	~~rejected~~	~~1307-1420~~	~~1667±56~~
~~6~~	~~5086~~	~~FV6-4/232-235~~	~~232.5~~	~~needles and leaves, small fragments~~	~~0.14~~	~~1045±70~~	~~rejected~~	~~778 – 1158~~	~~1489±56~~
~~7~~	~~4892~~	~~FV7/276-278~~	~~277~~	~~large wood fragment~~	~~0.99~~	~~960±35~~	~~rejected~~	~~1018 – 1158~~	~~1386±50~~
~~8~~	~~5087~~	~~FV8-3/308-310~~	~~311~~	~~small plant fragments~~	~~0.90~~	~~925±25~~	~~rejected~~	~~1032 – 1162~~	~~1308±43~~
~~9~~	~~4893~~	~~FV9-14/348-350~~	~~349~~	~~leaves, fragments~~	~~0.99~~	~~780±35~~	~~accepted~~	~~1190-1283~~	~~1220±30~~
~~10~~	~~5089~~	~~FV11-19/428-433~~	~~430.5~~	~~small plant fragments~~	~~0.61~~	~~1030±20~~	~~accepted~~	~~984-1026~~	~~1001±12~~

~~11~~	~~5090~~	~~FV12-2/444-446~~	~~445~~	~~small plant fragments~~	~~0.41~~	~~1140±20~~	~~accepted~~	~~777-977~~	~~953±20~~

No	**Lab code GdA-**	**Sample name**	**Depth (cm)**	**Material**	**Graphite mass (mg)**	**^{14}C age (BP)**	**Status and agreement index**	**Calibrated age ranges, unmodeled (AD)**	**Modeled age mean (AD) and 1 sigma**
1	4889	FV'-5/19-22	21.5	needles and leaves, small fragments	0.86	-1410±25	Accepted (A=64%)	68.2% probability 1985AD (68.2%) 1988AD 95.4% probability 1958AD (9.6%) 1959AD 1985AD (85.8%) 1988AD	1975±20
2	5084	FV3/57-59	58	leaf fragments	0.54	525±30	Rejected	68.2% probability 1400AD (68.2%) 1435AD 95.4% probability 1320AD (14.9%) 1350AD 1390AD (80.5%) 1445AD	1890±45
3	4890	FV'/62-64	63	large wood fragment	1.00	875±25	Rejected	68.2% probability 1150AD (68.2%) 1215AD 95.4% probability 1045AD (18.1%) 1095AD 1120AD (4.6%) 1140AD 1145AD (72.7%) 1225AD	1880±45
4	5085	FV15/114-115	114.5	needle fragment, small	0.25	470±50	Rejected	68.2% probability 1405AD (68.2%) 1465AD 95.4% probability 1320AD (4.8%) 1350AD 1390AD (87.1%) 1520AD 1595AD (3.5%) 1620AD	1760±60
5	4891	FV3-10/155-156	155.5	small wood fragment	0.61	570±25	Rejected	68.2% probability 1320AD (40.2%) 1350AD 1390AD (28.0%) 1410AD 95.4% probability 1305AD (57.6%) 1365AD 1385AD (37.8%) 1420AD	1665±65
6	5086	FV6-4/232-235	232.5	needles and leaves, small fragments	0.14	1045±70	Rejected	68.2% probability 890AD (68.2%) 1040AD 95.4% probability 780AD (1.3%) 795AD 805AD (2.6%) 845AD 860AD (91.5%) 1160AD	1490±65

7	4892	FV7/276-278	277	large wood fragment	0.99	960±35	Rejected	68.2% probability 1020AD (22.4%) 1050AD 1080AD (34.5%) 1125AD 1135AD (11.3%) 1150AD 95.4% probability 1015AD (95.4%) 1160AD	1390±60
8	5087	FV8-3/308-310	311	small plant fragments	0.90	925±25	Rejected	68.2% probability 1040AD (42.8%) 1100AD 1120AD (25.4%) 1155AD 95.4% probability 1030AD (95.4%) 1165AD	1310±50
9	4893	FV9-14/348-350	349	leaves, fragments	0.99	780±35	Accepted (A=72%)	68.2% probability 1220AD (68.2%) 1270AD 95.4% probability 1190AD (95.4%) 1285AD	1225±30
10	5089	FV11-19/428-433	430.5	small plant fragments	0.61	1030±20	Accepted (A=97%)	68.2% probability 990AD (68.2%) 1020AD 95.4% probability 980AD (95.4%) 1030AD	1000±15
11	5090	FV12-2/444-446	445	small plant fragments	0.41	1140±20	Accepted (A=90%)	68.2% probability 885AD (19.7%) 905AD 915AD (48.5%) 965AD 95.4% probability 775AD (3.1%) 790AD 805AD (1.1%) 820AD 825AD (2.3%) 845AD 860AD (88.9%) 980AD	950±25