Editor Decision: Reconsider after major revisions (20 Jun 2020) by Barbara Stenni
Comments to the Author:
Dear Dr. Bădăluță and Dr Perşoiu
The second version of your manuscript have been reviewed by the Ref1 and by another referee and both have indicated "reconsidered after major revisions".
There are three major drawbacks in my opinion and following both referees:
1. The dating
2. The comparison with other records
3. the structure of the manuscript

Dear Editor,

Thank you for your response. We were somehow dismayed by the apparent downward progression of our manuscript across revisions, hence our initial reaction and subsequent delay in response. Our renewed clarifications and response to the point-by-point queries are below. One more comment: please allow an overlap between the response to point 1 below and the response to queries by reviewer 3 on chronology.

Regarding the point 1. In the revised manuscript both referees found, and I agree with them, that you did not explain very well the reasons for rejecting a so high number of 14C data. These parts should be really improved. The lack of a robust chronology has a real implication to the second major drawback, the comparison with other records at a decadal scale for being able to look at the AMO variability. In the text you are using dates rounded at half a decade and with the uncertainty of the chronology that you have, I think that this is not possible. Perhaps the comparisons should be limited at the multidecadal-centennial time scale. One referee suggests two solutions to overcome this problem: further 14C dating with another technique or using the regional temperature records to maximize the correlation with the d18Oice over their common period.

We have mixed feelings when it comes to our chronology. We **know** it could be better, had more dates been available but we also know it is the best we could have obtained given the site constrains and our knowledge of ice caves processes. We break down our response in two: we first discuss issues related to incorporation of organic matter in ice and the construction of our chronology and second comparisons we carried out to test it.
We chose to report all ages we have obtained out of total openness, although we knew from the beginning that some of the samples we have analyzed could be problematic. These problems arise from the way organic matter is being trapped in ice. Large pieces of wood tend to cut through several layers of ice, sometimes encompassing decades worth of ice accumulation. This is because ice accumulation rates are in the order of mm-cm per year so that a tree trunk some 20 cm in diameter would take up to 50 years to be completely enclosed in ice. Thus ice immediately below it would be at least 50 years older than at its top. Further, ice melting and water freezing processes usually result in inclined ice surfaces and slow tipping of any large/heavy materials sitting on top of the ice (see the position of tree trunks in our fig. 1). Consequently, large pieces of wood could cut trough even more ice layers, so that depending on the position of the drilling site relative to that of a tree trunk, the age of ice could vary by (perhaps) 100 years. To complicate things further, not only large pieces of wood are problematic, but also small ones, detached from these and subsequently embedded in younger ice. The bottom line is that more often than not, ***old wood could get incorporated in younger ice***. The challenge is to identify and remove such potential datable organic material from any possible chronology but this somehow contrasts with the desire for precise chronologies, which rely on high number of data points. Thus, we decided to measure all possible samples although we knew that some would obviously give "wrong" ages. Following measurement, we have decided to remove those samples that were potentially coming from large pieces of wood, likely older than the surrounding ice. Fig. 2 shows that all rejected ages come from samples older than the accepted depth-age model. We tried a model to incorporate these ages but it resulted in a very long hiatus near the top of the ice core. We did not find any sign of such a hiatus.
Once we have constructed our chronology, we compared it with the only reliable one existing, published by Maggi et al in 2008. The ages published by Maggi are plotted in green in our Fig. 2 and there is abroad agreement between these and our model. Again, our rejected ages are older than also those of Maggi et al. (2008). Further, the same authors identified several potential markers of volcanic eruptions and their ages agree within ±40 years with those of our model. Third, we have compared our record with the stable isotope one of Kern et al., (2004) and Forizs et al. (2004). These authors drilled a core in FV in 2002, but lack of precise chronological control prevented further exploration of the data. However, a simple visual correlation between the records indicates a better than expected match between the two, except for the period between AD 1600-1750 (a period when we also see the largest

differences between our record and the AMO and we have the largest chronologic uncertainty – see our figure). We attach (an unpublished) simple figure with our and Kern's (2004) records.

One referee suggests two solutions to overcome this problem: further 14C dating with another technique or using the regional temperature records to maximize the correlation with the d18Oice over their common period.

We have dated all possible organic remains in the ice, and looking for more such samples means re-drilling the site. This would require a financial and logistic effort beyond our means at this point. Further, we have decided no to use ages from large pieces of wood – see the explanation above.
WIOC – we discussed this possibility, but dating WIOC gives extremely large errors (100-700 years, Uglietti et al., 2016, Moreno et al., 2020, Fang et al., 2020) and also needs larger amounts of ice to be melted (0.3-0.5 kg of ice, corresponding to between 10-30 cm long ice core sections) to obtain enough material for dating. We also discussed collecting DOC for dating purposes, but again decided against, for reasons similar to those discussed for WIOC (Fang et al., 2020).

We decided against using the regional temperature record to further anchor/improve our chronology. Our approach through the manuscript is as follows (and we will actually include this in the "Methods" section and in the final reorganized "Conclusions" section):

1. An independent chronology was constructed for the entire ice core
2. Observations on processes in the cave led us to hypothesize that both $\delta^{18}O$ and $\delta^{2}H$ are proxies for summer temperature
3. The $\delta^{18}O$ ($\delta^{2}H$) record was compared with instrumental data over the last 150 years to test the validity of the hypothesis
4. Parallel to this, both instrumental and paleorecords indicate that summer temperatures in our study are linked to SSTs in the North Atlantic (AMO)
5. We combined these to suggest that cave ice stable isotopes indicate that summer temperatures in East-Central Europe are linked to AMO variability

Using the instrumental record to improve our chronology would have resulted in a better age control for the upper part of the core but we would have lost the possibility to extend our analyses back in time as a result of a circular reasoning. We thus decided not to do it.

Regarding the point 2. In all the comparisons with other records you never use any statistics and I personally found difficult to follow all the dates in the text and at the same time looking at the different figures to follow the visual observations, that in some cases did not match at all. I am referring to figures 4, 6 and 7 and, in particular, to the following sections: page 6 lines 10-15; page 6, lines 38-42; page 7 lines 5-6. Several times I found that the periods you were referring to cold or warm periods were not evident from the figures at all. Please, check the dates!!! It is difficult to follow without some statistics. By the way, how did you define the 50-year lag of the d18Oice behind the AMO?

We did not use statistics to show strength of correlation for several reasons: 1) it is not common practice in the field (we surveyed all relevant papers published in CP in the past two years and found no such practice), 2) numerous arguments have been brought against false positive/false negative results, 3) given the different methods to establish the chronology of the various records we were using (14C dating, tree ring counting, calendar years) and the associated uncertainties, it is almost impossible to obtain results that would be meaningful beyond the already existing dating uncertainties. We further believe that all "correlations" should be based on physical (i.e,, climatic) mechanisms, rather than raw statistics.
We have improved all our relevant figures to support our findings; they now convey our message in a clearer way. In fig. 7, we have defined 8 cold periods and 7 warm periods. In the figure, the limits of these cold periods were not visual but identified at the intersection points between the line showing the $\delta^{18}O$ values and a straight line showing the average value over the entire period. These intersection points fall in any possible year (e.g., AD 928), however, at the suggestion of one of the reviewers, in the text we have rounded these to the nearest decade in order to account for the dating uncertainty – therefore slight discrepancies between the text and the figures might occur. We went again through the text and corrected the ages where errors occurred (e.g., while almost similar, small differences exists between the $\delta^{18}O$ and the $\delta^{2}H$ records (e.g., around AD 1750 and 1900) and these induced errors in our assessment).

I am referring to figures 4, 6 and 7 and, in particular, to the following sections: page 6 lines 10-15; page 6, lines 38-42; page 7 lines 5-6

Lines 38-42, where we defined the cold and warm periods were moved to the beginning of section 4.2. We present the cold and warm periods separately from any interpretation and subsequently discuss the potential correlations with solar minima, regional temperatures etc. The entire relevant sections have been rewritten.

By the way, how did you define the 50-year lag of the d18Oice behind the AMO?

We were not clear on this. Our data suggest that within dating uncertainties, the two records (ice core stable isotopes and AMO) are similar, except for the period AD 1600-1750, where we have a 50 years difference. This period is also the one with the highest uncertainty in dating (±50 years). We do not say that there is 50 years lag between the two, but that, between AD 1600-1750, due to dating uncertainties, there is a 50 years difference between the records. We clarified this in the text.

Regarding the point 3. There are several times in the manuscript, some paragraphs or sentences that seem to be in the wrong place. For example, at a certain point you are referring to the solar influence without explaining nothing at all before. The figure 6 and the its explanation comes after the figure 7. Some parts of the text in the discussion should be moved in section 3 (see comments by the referees). At a certain point you are referring to the solar minima and maxima without referring to any figure and without introducing your reasoning. All these weaknesses and lack of continuity make the reading very difficult.

We have clarified the text in all relevant sections. Indeed, the reference to solar influence was not well discussed and we have decided to remove it, as is could steer the discussion in a different direction (we discussed this in the early stages of writing and the text was left behind inadvertently).
The order of figures was corrected and we moved the suggested text to section 3.

Moreover, apart from what reported above, there are other questions, issues highlighted also by the referees, that would need your attention. You can find them in the referee's reports. Please, look at the them carefully. One of this, is the ice accumulation rate. There is not any associated figure and the last sentence of the paragraph (page 4, lines 34-36) as well as at page 4 line 27 ("The high accumulation rate …") does not agree with the results reported above (page 4, lines 19-21). One of the referees found that these data are overinterpreted, and I agree on this, or at least I was not able to follow.

We used the suggestion of referee 2 and completely rewritten the section on ice accumulations and reduced the potential interpretations to those that could have been matched to existing records in the region. A complete new paragraph replaced the old one, please see the main text.

One of the referees found that you did not demonstrate in the manuscript that the d18Oice of the FV cave is a summer temperature records contrary to what happen in other ice caves. The referee would suggest including in the manuscript the cave recording temperatures to see the time of the freezing. I think that more explanations and reasoning on the ice forming processes should be needed.

We have included a full explanation in the text, complete with references to cave climate monitoring data (these were published elsewhere and we did not include them here, but discuses them, nevertheless).

In the figure 4 the Summer temperatures of the stations show an increasing trend after 1980 AD. In the text (page 5, line 34) it is wrongly reported.

Indeed. We corrected 2000 to 1980.

The spatial correlation map (figure 5) does not show any correlation in your area (see green arrow in the figure). Please, explain better. Perhaps I miss the point.

Figure 5 shows the spatial correlation map between Sea Surface Temperature and average summer air temperature at one point location. The SST data is gridded data with values only over the sea/ocean. As such, colors refer to sea/ocean areas only, leaving land areas white. Strong (dark red) and significant (black hatching) are shown between regional land temperature and SST in the north Atlantic and the Eastern Mediterranean, both being the main sources of moisture delivered to the region.

In the text you are saying that you compared your FV record to the TRW record by Popa and Kern (2009) but in the figure 7 the TRW record is by Seim et al., 2012). Please, may you check?

Figure 7 shows both Seim et al. (2012) – panel d (TRW index) and Popa and Kern 2009) – panel e (summer temperature anomalies) data. We used the "TRW" acronym to refer to the "TRW-based summer temperature anomalies" but we have removed it to make the text clear on this.

The sentence at page 6 lines 35-37 seems a bit an over interpretation if you are not dealing with all the above points and explain better your reasoning.

We have reorganized the entire paragraph, It now reads:
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). The relationship between the FV $\delta^{18}O_{ice}$ and AMO records is strongest between AD 1125 and AD 1525 and AD 1750 and AD 2016, with decadal-scale variability in the two records being synchronous. Peak-to-peak matching of the FV $\delta^{18}O_{ice}$ and AMO records shows that during the past 1000 years the two records correlated well within the dating uncertainty (±30 years). However, between ~AD 1600 and 1750 (Fig. 6) peak-to-peak matching indicates a difference between the two records up ~ 50 years, likely the result of high (> 50 years) uncertainty in the ice core chronology between AD 1525 and AD 1750 (Fig. 6a).The overall correlations between 1) FV $\delta^{18}O_{ice}$ and instrumental summer temperature reconstruction over the past 150 years, 2) the instrumental (this study) and proxy-based (Nagavciuc et al., 2019a) correlations between summer air temperatures and AMO variability and 3) the correlations between the FV $\delta^{18}O_{ice}$ and AMO records over the past 1000 years 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.

At page 7 line 19 you are referring to millennial scale variability. Please rewords, the length of your record is about 1000 years.

Thank you for spotting this. It is „centennial" and we corrected the text.

Although I found your paper interesting, and I would really have liked to see it published I, found that at the present state this solution is not so easy. I think that there is still a lot of work to be done to improve this manuscript for being accepted in Climate of the Past, considering that we are already at the second round of revision. Nevertheless, I think that the ice cave deposits would deserve more attention in the paleoclimate community, particularly in regions where other paleoclimate archives are lacking.
So, what I am proposing, if you are still interested in publishing your manuscript in Climate of the Past, is that you really deal with ALL the comments above (some are from me) as well as all the referee comments. What I need to see, it is a real restructured manuscript, something more than a major revision. Otherwise I cannot accept the manuscript. When you will resubmit your revised version, I will send it again to at least one of the previous referees, and obviously there is no guarantee that the manuscript will be accepted at the end. I don't want to waste your time but the manuscripts in its present form is not acceptable and needs more working.
I kindly ask you to carefully check all relevant citations and references and add those pointed out by the referees. After restructuring your manuscript, you will probably need to rewrite the abstract and the conclusions.

Dear editor,
We went through the manuscript with your and the reviewers' comments at hand. We used them to guide us through the revision of the manuscript. Because the main issues were related to chronology, we paid particular attention to 1) explain how we derived the depth-age model of the ice core (in the responses) and 2) correct instances of the text where our inferences could have been based on data beyond the maximum acceptable dating error.
The text has been reorganized where it was not clear, and the conclusions (and also abstract) were rewritten. Overall, we believe that both our approach and data could form the basis of subsequent studies, supporting or contradicting our findings, but nevertheless advancing knowledge.

Thank you for your support and efforts.

Report 1

Review of Cave ice stable isotopes suggest summer temperatures in East-Central Europe are linked to AMO variability by Bădăluță et al.

This manuscript presents an interesting record from an ice cave in Rumania where the d18O data are interpreted as summer temperature variations in response to AMO variability during last 1000 years. Although the interest of this type of records is certainly high, the manuscript presents several issues that prevent its publication in Climate of the Past. I outline here my main concerns:

1) The most important problem is the lack of a robust chronology, specially to use this record as a reconstruction of an atmospheric-oceanic phenomenon such as the AMO that changes at a decadal scale. The chronology of this ice sequence, in spite of all the efforts carried out by the authors, is unfortunately not good enough for that comparison. The age-depth model is constructed by just 4 14C dates since up to 8 14C dates had to be discarded. The authors do not explain in detail the reasons to discard those ages but Fig2 shows the difficulties to construct a reliable age model for this sequence. Even if we consider that this is the best possible age model, it certainly lacks the chronological precision and accuracy to be later compared to total solar irradiance or tree-ring chronologies. If the authors decide to keep this chronology, I suggest to use the record to discuss variability at the scale of MCA vs LIA but not use it to compare with AMO variability.

Thank you for bringing up this point. One of the first two reviewers had similar concerns, and we did answer those to his satisfaction. Nevertheless, these new concerns help us future clarify our approach.

We have mixed feelings when it comes to our chronology. We **know** it could be better, had more dates been available but we also know it is the best we could have obtained given the site constrains and our knowledge of ice caves processes. We break down our response in two: we first discuss issues related to incorporation of organic matter in ice and the construction of our chronology and second comparisons we carried out to test it.

We chose to report all ages we have obtained out of total openness, although we knew from the beginning that some of the samples we have analyzed could be problematic. These problems arise from the way organic matter is being trapped in ice. Large pieces of wood tend to cut through several layers of ice, sometimes encompassing decades worth of ice accumulation. This is because ice accumulation rates are in the order of mm-cm per year so that a tree trunk some 20 cm in diameter would take up to 50 years to be completely enclosed in ice. Thus ice immediately below it would be at least 50 years older than at its top. Further, ice melting and water freezing processes usually result in inclined ice surfaces and slow tipping of any large/heavy materials sitting on top of the ice (see the position of tree trunks in our fig. 1). Consequently, large pieces of wood could cut trough even more ice layers, so that depending on the position of the drilling site relative to that of a tree trunk, the age of ice could vary by (perhaps) 100 years. To complicate things further, not only large pieces of wood are problematic, but also small ones, detached from these and subsequently embedded in younger ice. The bottom line is that more often than not, ***old wood could get incorporated in younger ice***. The challenge is to identify and remove such potential datable organic material from any possible chronology but this somehow contrasts with the desire for precise chronologies, which rely on high number of data points. Thus, we decided to measure all possible samples although we knew that some would obviously give “wrong” ages. Following measurement, we have decided to remove those samples that were potentially coming from large pieces of wood, likely older than the surrounding ice. Fig. 2 shows that all rejected ages come from samples older than the accepted depth-age model. We tried a model to incorporate these ages but it resulted in a very long hiatus near the top of the ice core. We did not find any sign of such a hiatus.

Once we have constructed our chronology, we compared it with the only reliable one existing, published by Maggi et al in 2008. The ages published by Maggi are plotted in green in our Fig. 2 and there is abroad agreement between these and our model. Again, our rejected ages are older than also those of Maggi et al. (2008). Further, the same authors identified several potential markers of volcanic eruptions and their ages agree within ±40 years with those of our model. Third, we have compared our record with the stable isotope one of Kern et al., (2004) and Forizs et al. (2004). These authors drilled a core in FV in 2002, but lack of precise chronological control prevented further exploration of the data. However, a simple visual correlation between the records indicates a better than expected match between the two, except for the period between AD 1600-1750 (a period when we also see the largest differences between our record and the AMO and we have the largest chronologic uncertainty – see our figure). We attach (an unpublished) simple figure with our and Kern’s (2004) records.

I outline here two possible improvements:

- The authors state that since the cave is open many organic remains reach the cave and are incorporated into the ice (they had more than 40 samples with organics). I suggest dating more samples. And, instead of looking for larger pieces of wood or leaves that are for sure more difficult to find, use the WIOC technique that requires a very small amount of carbon in the ice to be dated. Of course, some dates will provide reversals but some others, hopefully, will support the age model and will help to draw it with more certainty.

We have dated all possible organic remains in the ice, and looking for more such samples means re-drilling the site. This would require a financial and logistic effort beyond our means at this point. Further, we have decided no to use ages from large pieces of wood – see the explanation above.
WIOC – we discussed this possibility, but dating WIOC gives extremely large errors (100-700 years, Uglietti et al., 2016, Moreno et al., 2020, Fang et al., 2020) and also needs larger amounts of ice to be melted (0.3-0.5 kg of ice, corresponding to between 10-30 cm long ice core sections) to obtain enough material for dating. We also discussed collecting DOC for dating purposes, but again decided against, for reasons similar to those discussed for WIOC (Fang et al., 2020).

Fang, L., Jenk, T., Singer, T., Hou, S., and Schwikowski, M.: Radiocarbon dating of alpine ice cores with the dissolved organic carbon (DOC) fraction, The Cryosphere Discuss., 2020, 1-26, 10.5194/tc-2020-234, 2020.
Uglietti, C., Zapf, A., Jenk, T. M., Sigl, M., Szidat, S., Salazar, G. and Schwikowski, M.: Radiocarbon dating of glacier ice: overview, optimisation, validation and potential, The Cryosphere, 10(6), 3091–3105, doi:10.5194/tc-10-3091-2016, 2016.
Moreno, A., Bartolomé, M., López-Moreno, J. I., Pey, J., Corella, P., García-Orellana, J., Sancho, C., Leunda, M., Gil-Romera, G., González-Sampériz, P., Pérez-Mejías, C., Navarro, F., Otero-García, J., Lapazaran, J., Alonso-González, E., Cid, C., López-Martínez, J., Oliva-Urcia, B., Faria, S. H., Sierra, M. J., Millán, R., Querol, X., Alastuey, A., and García-Ruiz, J. M.: The case of a southern European glacier disappearing under recent warming that survived Roman and Medieval warm periods, The Cryosphere Discuss., 2020, 1-29, 10.5194/tc-2020-107, 2020.

- the other idea is using the regional summer temperature curve to maximize the correlation with the d18Oice, that is displacing the data from the ice within the chronological uncertainty until the correlation is maxima. Later, the authors can present how much towards the past or towards the present they had to move the d18Oice data and see if this is still coherent with the age model. To do that, better evidences that the d18Oice is a proxy for summer temperatures are needed (see point 2)

While tempting, we decided against it, in order to prevent any circular reasoning.

2) This record is presented as a summer record instead of a winter one (as A294 ice cave in Spain or Scărișoara cave in Romania). The main argument is that the water that penetrates directly from the open ceiling of the cave freezes during early fall (not late fall-early winter as the other caves do) thus preserving the summer signal in the isotopes. This is probably true, but not demonstrated in the manuscript. I include here some ideas:
- I am pretty sure the authors have some sensors in the cave recording temperatures. Is it possible to see the time of the freezing? Is it always the same every year? Is it changing?
- Have you sampled the ice body surface during last 20 years? In the manuscript there is a sentence that seems to indicate that. If so, it will be excellent to see those data and their relationship with summer temperatures of that year. The comparison during instrumental period presented in Fig. 4 is nice, but the d18Oice from FV ice cave is plotted using the chronology presented here and for the last 150 years, I am afraid there is just one 14C date.

Contrary to high altitude ice caves in which ice forms through the diagenesis of snow accumulated in winter (A294 in Spain, caves in the Austrian Alps and Croatian Dinaric Mts. etc), ice in caves in the Carpathians Mountains (Scarișoara, Focul Viu, Bortig in Romania, Dobsinska and Demanovska in Slovakia etc) form through freezing of water accumulated during summer and autumn months. The timing of the onset of freezing depends on a delicate balance between cave morphology and local climate, varying between September and December. These being said, for the case here, freezing starts in early autumn, when the large opening in the ceiling allows descent of cold nocturnal air (literally a cold air avalanche) that sweeps the cave leading to freezing of the upper layer of water standing on the ice. Although temperatures may rise above 0 °C during September (and sometimes October), they nevertheless are not high enough to melt the already formed ice. Subsequent cooling episodes result in further freezing of water and ultimately formation of the annual layer of ice out of water that has accumulated between late spring and late-summer (possibly also early autumn). We have monitored air temperature for several years, with the

early data published in 2007 (Perșoiu et al., 2007). This monitoring and our observations over the past 15 years have shown that the onset of freezing occurs no later than mid-September.
We have subsequently expanded the text of the article to better explain the mechanisms of cave ice formation.

Sampling the upper layers of ice and comparisons of $\delta^{18}O$ (or $\delta^{2}H$) with measured air temperature: because the accumulation of ice is not a continuous process (i.e., in years with warm and/or wet summers, ice formed in the previous year could partially or totally melt), reconstruction of annual $\delta^{18}O$ variability in ice) to be compared with instrumental temperature data) is not possible. Over, say 10-20 years, missing just two or three years would make any comparison with instrumental data meaningless. This is further complicated by the fact that we cannot realistically expect a perfect match between measured air temperature and reconstructed air temperature using the δ18O-air temperature relationship. The combination of these two facts would thus make such an approach more problematic than less useful.
However, our figure four shows that a very good correlation exists between $\delta^{18}O_{ice}$ and both instrumental temperature data and AMO on decadal time scales. The chronology is based on our depth-age model and we believe that the best approach would be to 1) asses these correlations using an independent chronology for the time period covered by instrumental data and 2) use it on an independently-dated core. We are keeping this in mind and will use it our future work (we are adding this proposed approach to our main manuscript so that it could be also used by potential readers). In the context of 1) inherent chronological uncertainties associated with ^{14}C dating (±30 years), AMO scales of variability (20-30 years long (potential) periodicity and 3) ice cave processes, with successive accumulation and melting episodes resulting in the loss of annual signal, we believe that the correlation displayed in fig. 4 of our manuscript is satisfying and strongly indicates a potential link between $\delta^{18}O_{ice}$ and local and regional climatic conditions.

3) Finally, I find very appealing the comparison with other records in CEE during last millennium. This comparison is mostly presented in Fig.7 and in the second part of the Discussion section. I miss there some statistics, specially about the correlation among records. Those correlations are just based on visual observation and this is not enough, I think.

Indeed, there are many, many records out there that could have been used for comparison purposes. We decided which one to use based on the following principles: 1) the archives should record summer temperature variability, only; 2) the records should come from regions that show a high correlation between summer air temperature and AMO (as this is what we've been discussing). We have further used tow regional records that capture a continental-scale signal, thus free of local influences. To emphasize the later point, we included a new figure in our articles with the location of our chosen sites superimposed on the map showing the strength of the correlation between JJA AMO and JJA air temperature.
Further, we have decided not to use statistic, and it is extremely unreliable when comparing records of different length, resolution and dating uncertainty. This approach is also not used in the community when prox-based records are being analyzed, for the same reasons (some 20 papers published in 2019 and 2020 in CP did not use this statistics to support proxy comparisons).

Report 2
Dear Authors,

Thanks for your answers and I appreciate your effort how revised your work. I think this is undoubtedly an improved version compared to the initial one. I accept your reasoning why not modify the original depth data. I accept also the solution using a uniform age distribution from 1991 to 2016 AD for the core top in age depth modelling and satisfied also with the revised Table 1.

Thank you for the positive appreciations.

However, I feel some further changes and clarifications are still needed before publication. I think the data are interesting so I encourage the Authors for further revision.

Major comments:
-Section 3.2. Please give quantitatively the carbon yield needed for AMS analysis. For instance, the 0.14 mg graphite yield of GdA-5086 (FV6-4/232-235) seems to be close to the critical mass which might explain why it

produced an outlying old age. In addition, in your response you agreed with my comments related to old bias for large wood (you wrote:" As correctly pointed out by the reviewer, this was the reason behind rejecting the sample at -63 cm") however I haven't found it in the revise manuscript. In general I suggest giving more word explaining the preselection of the samples entered or excluded from age-depth modelling. Maybe you could replace a part of section 4.1 with this issue (see next comment).

Indeed, the 0.14 mg of graphite is at the limit of AMS dating in the Gliwice Radiocarbon Laboratory. However, we have undertaken all necessary measures to ensure this date is reliable, like treatment and measurement of Oxalic Acid II standard and blank samples of similar mass, which were used for 14C age calculations.

We have added a paragraph about sample selection and our strategy of age-depth model construction.

- I'm afraid the discussion of temporal differences of ice accumulation rate is a bit over interpretation. There are rather few control points (5 including the top of the core) and the finally accepted age-depth model do not suggest any remarkable change in ice accumulation rate. To be on the safe side I'd suggest reporting only the long-term mean ice accumulation rate and discuss only its comparison to other multicentennial mean cave ice accumulation rates from the surroundings. A related point is that you reported the largest accumulation rate (0.56 cm/years) for the past 40 years. It is in strong contrast compared to experiences from other ice caves from the Carpathians (or Europe).

The entire section has been rewritten and the results put in a wider regional context. In now reads:
"High accumulation rates were recorded between AD 850 and 950 (0.39-0.41 cm/year) and between AD 1220 and 1970 (0.36-0.44 cm/year). Between AD 950 and 1220, the net accumulation rate dropped to between 0.29 and 0.34 cm/year. The highest net accumulation rates recorded after AD 1970 (0.56 cm/year) contradict recent findings from other ice caves in the Carpathian Mountains (Kern and Perşoiu, 2013), which all register record melting. However, this value might be an artifact of the depth-age modeling (see above) as well as of the very short time span considered, thus being unreliable for further interpretation. The low accumulation rates spanning the MWP are similar to those recorded in Scărișoara Ice Cave (Perşoiu et al., 2017, Bădăluță, 2019), Hundsalm Ice Cave in Austria (Spötl et al., 2014) and ice caves in Velebit Mountains, Croația (Kern et al., 2018), suggesting a possibly regional signal of climatic conditions unfavorable for ice accumulation. 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 across the top of the ice block. Subsequently, ice growth is influenced by the amount of water present at the onset of freezing, the timing of this onset and its duration. The low accumulation rates during the MWP were likely the result of enhanced melting during warm (see section 4.2 below) and wet (Feurdean et al., 2015) conditions. After AD 1450, the climate in the region was dominated by dry summers with frequent storms and cold winters (Perşoiu, 2017). These conditions lead to reduced summer melting and enhanced winter growth, thus conditions favorable for net ice accumulation."

- some parts of the discussion should move to Methods (see detailed comments below)
We identified (thank you) and moved the relevant sections (see below).

Specific comments:
Page 2 lines 41-43: reference is needed for AMO.

The following references have been added:
Schlesinger M. E. & Ramankutty N. An oscillation in the global climate system of period 65–70 years. Nature 367, 723–726 (1994).
Kerr R. A. A North Atlantic climate pacemaker for the centuries. Science 288, 1984–1985 (2000).
Kaplan A., Cane M. A., Kushnir Y. & Clement A. C. Analyses of global sea surface temperatures 1856–1991. J. Geophys. Res. 103, 18,575–18,589 (1998)
Knudsen, M. F. *et al*. Tracking the Atlantic Multidecadal Oscillation through the last 8,000 years. *Nat. Commun.* 2:178 doi: 10.1038/ncomms1186 (2011).

Page2 line11: Stoffel et al. 2009 (https://doi.org/10.1016/j.yqres.2009.03.002) could be also cited as an example when changes in cave ice accumulation rate was used as indicator of past climate variability.

Done

page2 line 19: Bella and Zelinka 2018 (https://doi.org/10.1016/B978-0-12-811739-2.00029-2) should be also cited supporting the statement that "The Carpathian Mountains host several ice caves"

Done

page2 lines 31-35 These statements are supported by the air temperature monitoring of Focul Viu Ice Cave (Perşiou et al. (2007) Preliminary data on air temperature in Focul Viu Ice Cave (Bihor Mts, Romania). In: Zelinka, J. (ed.) Proceedings of the 2nd International Workshop on Ice Caves, Liptovský Mikuláš, pp.62-64.).

Done

page4 lines16 please consider rephrasing "dating of organic remains and 1100 cal BP at 4.86 m below surface (extrapolation)." to "dating of organic remains (Table 1) and extrapolated as 1100 cal BP at 4.86 m below surface."

Done

page4 line 16-18. This sentence should go to section 3.1.

Indeed. We moved the sentence to the section describing drilling.

page5 line 13 Please rephrase this sentence. It is a bit strange reading that records show "stable values" when you write about stable isotope ratios. Perhaps you could write that there is no trend.

Corrected. The text now reads „The FV $\delta^{18}O_{ice}$ and $\delta^{2}H_{ice}$ records span the AD 850 – AD 2016 period. Decadal to multi-decadal scale oscillations occur over the entire record, but no discernable long-term trend was identified."

page5 lines 27-32 Station description should go to Section 3.3. Maybe you could mark these stations in Fig1a.

We added text to section 3.3 and inserted the position of stations in Fig. 1.

page5 lines 36-40 This is mainly methodological description. I think it should also go to Section 3.3.
Done.

page6 lines 1-2 I think the statement about extreme high temperatures and AMO could be omitted since extreme high temperatures were not assessed in this study.

We have reformulated the sentence, based on the reference we are citing (Della-Marta et al., 2007). It nwo reads: "These results are also in agreement with the results of Della-Marta et al. (2007), showing that summer positive temperature anomalies and heatwaves over Europe are triggered, at least partially, by the phase of AMO."

page6 line 7-8 How could enhanced ice melting lead to high δ18O values? Maybe this needs more explanation.

It doesn't, of course. This was a mistake carried over from combining two different sentences and not checking the final result. Nevertheless, we have rewrote the text to make it clear, see below:

"Thus, we suggest that, during summer, strongly meandering Rossby waves (Ioniță, 2015, 2017) result in blocking conditions over Central Europe that lead to the persistence of high-pressure systems and occurrence of regional heat waves. These, in turn, favor regional recycling of moisture resulting in positive $\delta^{18}O$ anomalies in precipitation that are further recorded by cave ice (this study) and tree rings (Popa and Kern, 2009; Nagavciuc et al., 2019a). Increased contribution of recycled moisture to precipitation has been reported in Central Europe, further supporting our inference (Gómez-Hernández et al., 2013; Kern et al., 2020).”

page6 line 11 Please, add “from the Eastern Carpathians” between “anomalies” and the citation. In addition, please, keep in mind that the cited study developed summer temp reconstruction only from 1163 AD so you should not cite it for cold or warm periods before this date.

Done

page6 line 21. “solar influence” mentioned at the end of this sentence is somehow astounding. The explanation is only in lines 35-38. Maybe some rearranging could be useful here.

We have rephrased the text considering this suggestion, as well as those of the editor to read:
“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). The relationship between the FV δ18Oice and AMO records is strongest between AD 1125 and AD 1525 and AD 1750 and AD 2016, with decadal-scale variability in the two records being synchronous. Peak-to-peak matching of the FV δ18Oice and AMO records shows that during the past 1000 years the two records correlated well within the dating uncertainty (±30 years). However, between ~AD 1600 and 1750 (Fig. 6) peak-to-peak matching indicates a difference between the two records up ~ 50 years. This apparent lag”

page6 line 26 Please consider inserting “in the ice core chronology” between the words “uncertainty” and “between”

Done

page 6 line 39-40 The first period mentioned as low and high δ18O values overlap. Please check the dates.

Corrected. „ low δ^{18}O values …. being around AD 875-930”

Cave ice stable isotopes suggest summer temperatures in East-Central Europe 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 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~~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~~ radiocarbon dated record of summer temperature variations during the last millennium in ECE, based on stable isotope~~ic~~ analysis ~~performed on~~of 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.~~ Comparisons with both instrumental and proxy-based data indicate that the stable isotope composition of cave ice records changes in summer air temperature and ~~is~~has a similar temporal evolution as ~~to~~ that of the Atlantic Multidecadal Oscillation on decadal to multi-decadal times scales, suggesting that solar-induced changes in the North Atlantic are transferred, likely *via* atmospheric processes towards the wider Northern Hemisphere. On centennial time scales, the data shows little summer temperature differences between the Medieval Warm Period (MWP) and the Little Ice Age (LIA) in Eastern Europe. Th~~i~~ese findings are ~~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.~~ c~~C~~ontrary to those that show a marked contrast between the two periods in terms of both ~~summer temperatures,~~ winter and annual ~~ones show stronger contrast between the MWP and LIA~~air temperatures, suggesting that the cooling associated with the LIA was likely the result of mainly winter time climatic changes.. ~~thus suggesting that the later were likely an expression of winter climatic conditions.~~

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1 Introduction

Rapid 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 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 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. 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). These 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 seasonally distinctive climatic changes (e.g., Ljungqvist et al., 2019), as these are responding to different forcing mechanisms (e.g., Perşoiu et al., 2019). On multidecadal time scales, summer climate over Europe is influenced, mainly, by the Atlantic Multidecadal Oscillation or (AMO (Schlesinger et al., 1994; Kaplan et al., 1998; Kerr, 2000; Knudsen et al., 2011, 2014). The AMO is a climate mode of variability associated with periodic 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 summer (Sutton and Dong, 2012; Ioniţă 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 Perşoiu, 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, Stoffel et al. (2009), Perşoiu 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; Perşoiu et al., 2020). 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 (Perşoiu et al., 2011a, 2011b). The Carpathian Mountains host several ice caves (Bella and Zelinka, 2018; 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; Perşoiu et al., 2017). 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 $\delta^{18}O$ and $\delta^{2}H$ values measured along an ice core drilled in Focul Viu Ice Cave (Western Carpathian Mountains, Romania).

2 Site information

Focul Viu Ice Cave (FV, 107 m long, ~30 m deep) is located in the Central Bihor Mountains, Romania (46.27 °N; 22.68 °E, 1165 m above sea level, Fig. 1a, Perşoiu 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 (Little Hall, 20 × 5 m). The ceiling of the Great Hall opens to the surface (Fig. 1c) allowing 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 air circulation (Perşoiu 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 result of this air circulation, between October and April the dynamics of air temperature inside and outside of the cave follow a similar pattern while between May and September the temperatures are stable at 0 °C (Perşoiu et al., 2007).

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 to form a layer of water, approximately 0-20 cm deep. Monitoring of air temperature in the cave has shown that in early autumn (September) air temperature drop below 0 °C outside the cave leading to cold air avalanches reaching the inner parts of the cave (Perşoiu et al., 2007). The inflow of cold air leads to the freezing of the lake water from top to bottom, forming~~and at the onset of negative temperatures in September it starts to freeze forming~~ a 1-20 centimeter~~m~~ thick layer of ice (*summer ice*). Although air temperature might briefly raise above 0 °C in autumn, temepartures inside the acve do not rise above 0 °C. Thus the layer of ice formed on top of the lake will prevent subsequent addition of water to the lake, so that it will preserve the original comsposition of summer precipitation. Infiltration and subsequent freezing of water during warm periods in winter results in additional layers of ice on top of the ice block (*winter ice*). However, a~~A~~t the onset of melting~~ in April/May~~, this winter ice melts (Perşoiu et al., 2011b). 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. Inflow of warm water in wet summers leads to rapid ablation of the ice at the top of the ice block, partly altering the annual layering. The processes 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) have been described from the nearby Scărişoara Ice Cave (Perşoiu and Pazdur, 2011; Feurdean et al., 2011) and, given the similarities between the two caves, are also pertinent to Focul Viu Ice Cave. The one notable difference is the timing of the onset of freezing: in Scărişoara 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. 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 core was cut into 1 cm layers considering also the annual layering in a cold room, except for the section between 290 and 320 cm below surface, where we intercepted a tree trunk. Each sample was sealed in a plastic bag, allowed to melt at room temperature, transferred to a 20 mL HDPE scintillation vial 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.

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 0.1~~6~~ ‰ for $\delta^{18}O$ and 0.5~~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 (Fig. 1c) allows for a large volume of organic matter to fall into the cave and subsequently become trapped in the ice, including large pieces of wood, which tend to cut through layers of ice, sometimes encompassing decades of ice accumulation. Furthermore, ice melting and water freezing processes usually result in inclined ice surfaces and slow tipping of any heavy materials sitting on top of the ice (see the position of tree trunks in Fig. 1). The "old wood effect", resulting in sample ages much older than the ice layers was expected. However, the challenge to identify such organic material contrasts with the desire for precise chronologies, which rely on high number of data points. Thus, all possible organic samples were recovered and dated, and unreliable ages identified at the stage of age-depth modellingmodeling were removed. Out of During drilling, we recovered over 40 samples of organic matter from large tree trunks to pieces of leaves.14 samples recovered from the ice core and -Only 14 were spotentially suitable for radiocarbon dating, of which two2 were not datable due to their extremely small carbon yield. AMS radiocarbon analyses were performed at the Institute of Physics, Silesian University of Technology, Poland (Piotrowska, 2013). All samples were precleaned with standard acid-alkali-acid treatment, dried and subjected to graphite preparation using an AGE-3 system (IonPlus, CH) equipped with an Elementar VarioMicroCube 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 of comparable carbon masses were measured by the DirectAMS laboratory, Bothell, USA (Zoppi et al., 2007). The results are reported in Table 1. The radiocarbon dates were calibrated using OxCal v4.3 (Bronk Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013). The NH1 curve (Hua et al., 2013) was used for one post-bomb date.

Because 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 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 1991 to 2016 AD was assigned, allowing for the possibility of surface ice melting. 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 a depth of 4.86 m. The agreement index of the model was 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 in Table 1.

-The constructed age-depth model was compared it with the only reliable one existing for Focul Viu, published by Maggi et al. (2008), which is plotted in green in Fig. 2 and prove a broad agreement of both chronologies. As expected, our rejected ages are older than those of Maggi et al. (2008). Further, the same authors identified several potential markers of volcanic eruptions and their ages agree within ±40 years with those of our model. Another evaluation was obtained by comparison of our stable isotope record with the one of Kern et al. (2004) and Forizs et al. (2004), and although the latter lack a precise chronology, a simple visual correlation between the records indicates a satisfactory match between the two records. In order to avoid any circular reasoning, we decided against numerical use of other records, e.g. the regional temperature record, to further anchor our chronology. For the top of the ice core a uniform age distribution from 1991 to 2016 AD was assigned, allowing for the possibility of surface ice melting. 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 a depth of 4.86 m. The agreement index of the model was 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 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 s~~Station-based meteorological data was provided by the Romanian National Meteorological Administration for three stations (Baia Mare, Sibiu and Timişoara) that have some of the longest instrumental records in Romania and are bracketing the location of the study site.~~.~~ To remove short-term variability and retain only the 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.

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 age-depth model shown in Fig. 2. The maximum age of the ice is 1000±20 cal BP at 4.45 m below surface, based on direct dating of organic remains ~~and~~ (Table 1) and extrapolated as 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).~~

High accumulation rates were recorded between AD 850 and 950 (0.39-0.41 cm/year) and between AD 1220 and 1970 (0.36-0.44 cm/year). Between AD 950 and 1220, the net accumulation rate dropped to between 0.29 and 0.34 cm/year. The highest net accumulation rates recorded after AD 1970 (0.56 cm/year) contradict recent findings from other ice caves in the Carpathian Mountains (Kern and Perşoiu, 2013), which all register record melting. However, this value might be an artifact of the depth-age modeling (see above) as well as of the very short time span considered, thus being unreliable for further interpretation. The low accumulation rates spanning the MWP are similar to those recorded in Scărişoara Ice Cave (Perşoiu et al., 2017, Bădăluţă, 2019), Hundsalm Ice Cave in Austria (Spötl et al., 2014) and ice caves in Velebit Mountains, Croaţia (Kern et al., 2018), suggesting a possibly regional signal of climatic conditions unfavorable for ice accumulation. 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 across the top of the ice block. Subsequently, ice growth is influenced by the amount of water present at the onset of freezing, the timing of this onset and its duration. The low accumulation rates during the MWP were likely the result of enhanced melting during warm (see section 4.2 below) and wet (Feurdean et al., 2015) conditions. After AD 1450, the climate in the region was dominated by dry summers with frequent storms and cold winters (Perşoiu, 2017). These conditions lead to reduced summer melting and enhanced winter growth, thus conditions favorable for net ice accumulation.

~~The ice accumulation rate was 0.39-0.41 cm/year between AD 850 and 950, 0.29-0.37 cm/year between AD 950 and AD 1000, 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 across the top of the ice block. Subsequently, ice growth is influenced by the amount of water present at the onset of freezing, the timing of this onset and its duration. Thus, the resulting accumulation rate is a record of the complex interplay of these climatic conditions, being an indicator of both ice growth and melt. The high accumulation rates registered between AD 810 and AD 1230 were likely the result of greater amounts of water available in the cave during the generally wet conditions of the Medieval Warm Period (Feurdean et al., 2015). The~~

highest accumulation rates were recorded between AD 1230 and AD 1400, a period of enhanced Mediterranean moisture transport to the site and slightly warmer winters compared to the preceding and ensuing periods. 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 (Perşoiu 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 summers with frequent storms and cold winters (Perşoiu, 2017). These conditions lead to low amounts of water available for freezing in early autumn and thus no winter ice accumulation as well as enhanced summer melting, a combination of processes resulting in minimal ice accumulation.

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 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 minimum (-19.8 ‰ and -140 ‰, for $\delta^{18}O$ and $\delta^{2}H$, respectively) in January. Similar result 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 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 very similar to those 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), defined as $d = \delta^{2}H - 8*\delta^{18}O$ (Dansgaard, 1964) allows for a clear separation of the air masses: Atlantic ocean (d-excess close to the global average of 10 (Craig, 1961)) 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 southwest Romania and Bădăluță et al. (2019) in precipitation in northeast Romania and linked to air masses originating in the strongly evaporated Mediterranean and Black seas, respectively.

The FV $\delta^{18}O_{ice}$ and $\delta^{2}H_{ice}$ records span the AD 850 – AD 2016 period. Decadal to multi-decadal scale oscillations occur, showing generally stable values low variation of values over throughout the entire analyzed periodrecord, on whichbut no discernable long-term trend was identified decadal to multi-decadal scale oscillations are superimposed. Several periods of excursions towards low $\delta^{18}O$ values (defined as $\delta^{18}O_{ice}$ below the long term average, suggesting low summer temperatures) dot the past 1100 years at AD 875-930, AD 1050-1080, AD 1260-1330, AD 1430-1480, AD 1520-1550, AD 1710-1750, AD 1820-1870, AD 1880-1930. Significant maxima in the FV $\delta^{18}O_{ice}$ record occurred between AD 850-870, AD 1000-1050, AD 1080-1260, AD 1350-1390, AD 1480-1520, AD 1625-1710, AD 1950-1970 (Fig. 7). Both $\delta^{18}O_{ice}$ and $\delta^{2}H_{ice}$ records display a remarkable similarity throughout the entire period and in our discussion we have used relied on the only $\delta^{18}O$ record, only.

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 summer. 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 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 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, several studies have shown (e.g., in the nearby Scărișoara Ice Cave (Perșoiu 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 Timişoara (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 1980AD 2000, and enhanced warming over the last two four 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). 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 the 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). The strongest correlations (Fig. 5) are found between SSTs in the North Atlantic and the Eastern Mediterranean Sea, both being the main sources of moisture feeding local precipitation (Bădăluță et al., 2019). These results are also in agreement with the results of Della-Marta et al. (2007), showing that summer positive temperature anomalies and extreme high temperaturesheatwaves 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). Thus, we suggest that, during summer, strongly meandering Rossby waves (Ionita et al., ță, 2015, 2017) result in blocking conditions over Central Europe that lead to the persistence of high-pressure systems and occurrence of regional heat waves. These, in turn, favor regional recycling of moisture resulting in positive $\delta^{18}O$ anomalies in precipitation that are further recorded by cave ice (this study) and tree rings (Popa and Kern, 2009; Nagavciuc et al., 2019a). Increased contribution of recycled moisture to precipitation has been reported in Central Europe, further supporting our inference (F ńl dy-Gdqḿndez et al., 2013; Kern et al., 2020). 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 related to prolonged warm SST in the North Atlantic Ocean, lead to high $\delta^{18}O$ values in the FV ice core via enhanced ice melting, while prolonged cold summers related to a cold North Atlantic Ocean, lead to low $\delta^{18}O$ 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-based (TRW) reconstruction of summer (JJA) temperature anomalies from the Eastern Carpathian Mountainss (Popa and Kern, 2009). The highest similarities between the FV ice core and TRW recordssummer temperature records were found for the cold periods between AD 12601330AD 1000 – 1050, 1250 – 1300, AD 1430-14801420 – 1680, AD 1520-1550 1750 – 1850 and AD 1820-1870 1960 – 1980 and the warm periods during AD 1080 – 12600, AD 1625-1710, AD 1950-19701850 – 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 tree rings and $\delta^{18}O$) and of the chronologies (annual tree ring counting vs. ^{14}C dating with a ± 30 years error), 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 1125 and AD 1525 and ~~~~~AD 1750 and AD 2016~~ and between AD 1125 and AD 1525~~, with decadal-scale variability in the two records being synchronous. Peak-to-peak matching of the FV $\delta^{18}O_{ice}$ and AMO records shows that during the past 1000 years the two records correlated well within the dating uncertainty (±30 years). However, ~~within the dating uncertaint~~b~~y~~etween ~AD 1600 and 1750 (Fig. 6) peak-to-peak matching indicates a difference between the two records up ~ 50 years, ~~(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~~ likely the result~~ed from 1)~~of high (> 50 years) uncertainty in the ice core chronology between AD 1525 and AD 1750~~, as well as before AD 1125~~ (Fig. 6~~7~~a).The overall correlations between 1) FV $\delta^{18}O_{ice}$ and instrumental summer temperature reconstruction over the past 150 years, 2) the instrumental (this study) and proxy-based (Nagavciuc et al., 2019a) correlations between summer air temperatures and AMO variability and 3) the correlations between the FV $\delta^{18}O_{ice}$ and AMO records over the past 1000 years ~~; 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 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 8750-930, AD 1045-1080, AD 1270-1325, AD 1430-1475, AD 1525-1550, AD 1715-1730, AD 1820-1865 and AD 1880-1925. Significant maxima occurred between AD 850-875, AD 1010-1030, AD 1350-1390, AD 1485-1510, AD 1625-1695 and AD 1950-1970. 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 (e.g., Buntgen et al., 2011) at regional and hemispheric scale (Fig. 7). Further, regional summer temperature (e.g., Popa and Kern, 2009) 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 with erratically distributed precipitation. Together, these data suggest a complex picture of climate variability in the wider Carpathian region, with much of the yearly temperature variability during the past 1000 years being attributed to the

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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 (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~~in East-Central Europe. Comparison of ice core δ^{18}O (and δ^{2}H) with instrumental data over the past 150 years indicates that the stable isotope composition of cave ice records summer air temperatures on multidecadal time-scales. Given the strong relationship between the instrumental temperature records and both instrumental and proxy-derived records of the Atlantic Multidecadal Oscillation (AMO) we further suggest that $\delta^{18}O_{ice}$ in Focul Viu Ice Cave ~~is a potential proxy for~~can be used to infer past AMO variability. W~~we~~ subsequently hypothesize that solar-induced changes in summer climatic conditions over the Northern Atlantic are transferred through atmospheric processes across the Northern Hemisphere, influencing summer temperatures across Europe. The ~~. Similar records are thus required to test this hypothesis.The~~ data shows little ~~millennial~~centennial-scale summer temperature variability since the onset of the Medieval Warm Period and through the Little Ice Age. Nevertheless, well-expressed minima and maxima occurred synchronously with data from other records in the region and through Europe, suggesting that the stable isotope composition from cave ice records a regional climatic signal. Contrary, winter air temperature records from the region indicate colder conditions during the LAI compared to the MWW, pointing towards a seasonally distinct climatic signal during these two periods. This suggests that forcing factors acting seasonally had a strong imprint on temperature variability, overriding long-term, global forcing.

Our results offer a potential hypothesis to be further tested by extending this and similar records back in time and also incorporate other proxy-base reconstructions to investigate the spatial extent of the influence of North Atlantic climate further east.~~Nevertheless, well-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 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.~~

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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 δ^{18}O and δ^{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 and e was downloaded from the NOAA/World Data Service for Paleoclimatology webpage.

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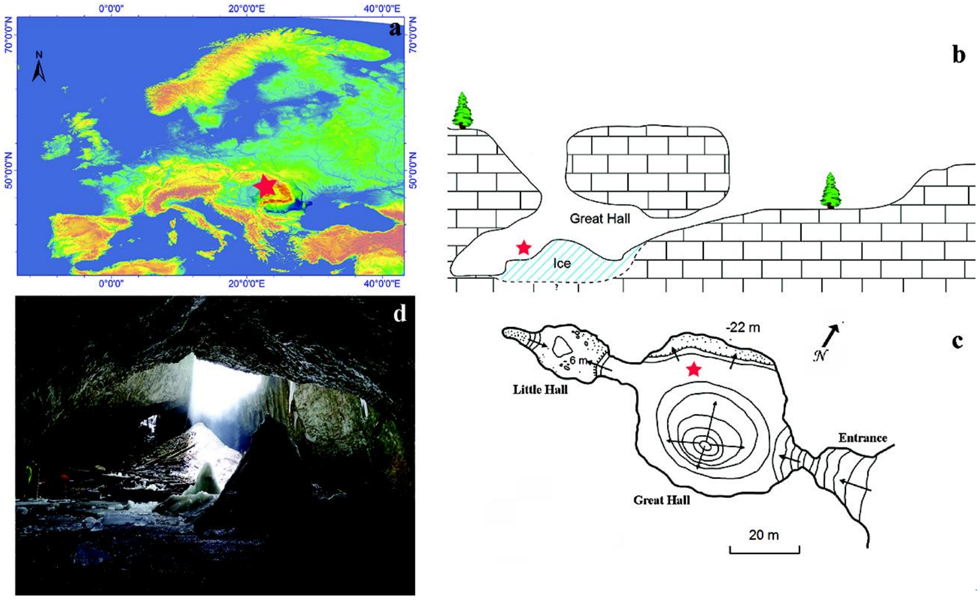


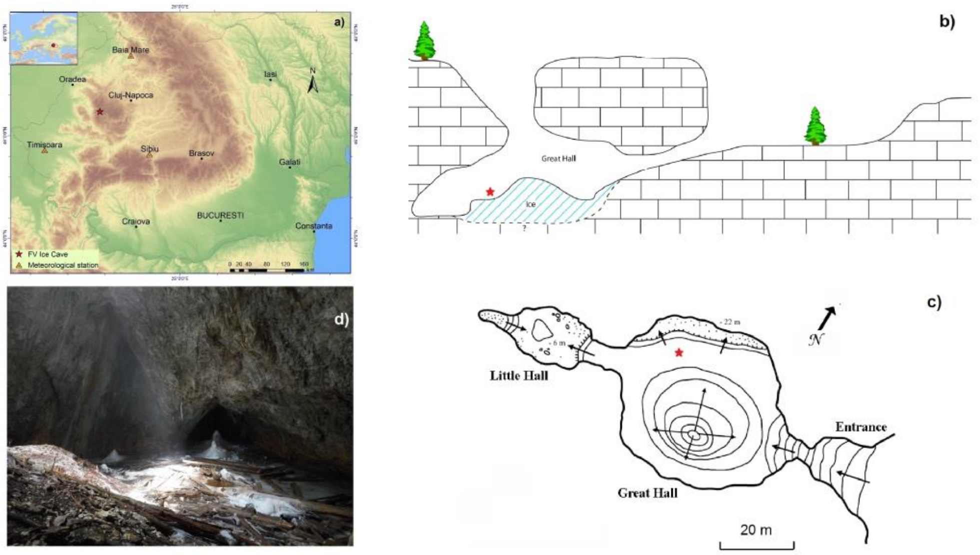


Figure 1. Location of the Focul Viu Ice Cave (red star) in Europe (a),cross section (b) and map (c) of the cave (red star indicates the drilling site) and (d) general view of the Great Hall (person in yellow on the left is standing at the drilling site).

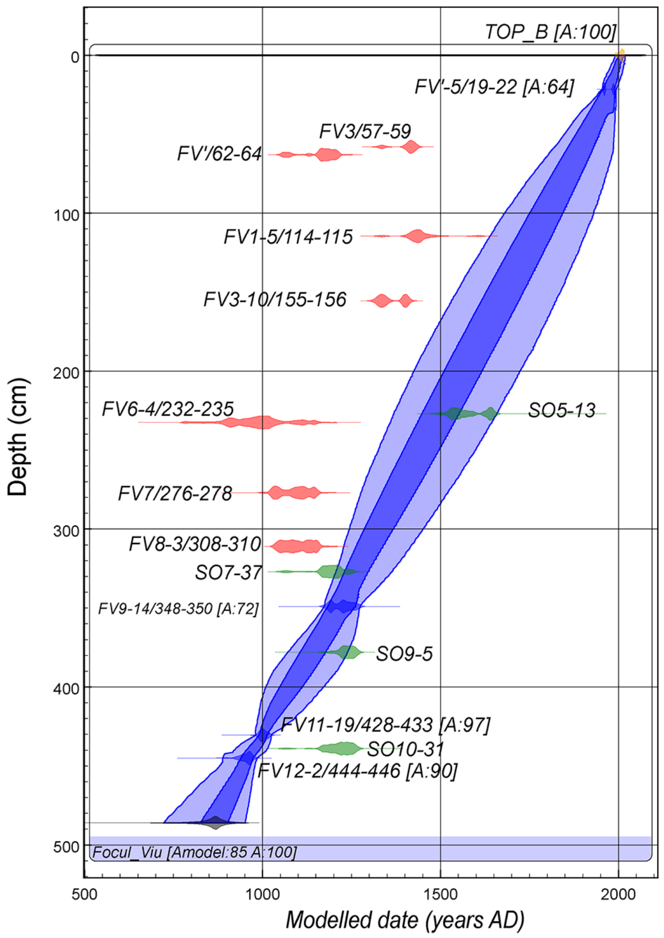


Figure 2. Age-depth model of the Focul Viu ice core. The calibrated age range of samples used in the model is indicated in blue and for those rejected, in red. Samples in green are from the ice core drilled in 2004 (Maggi et al., 2008).

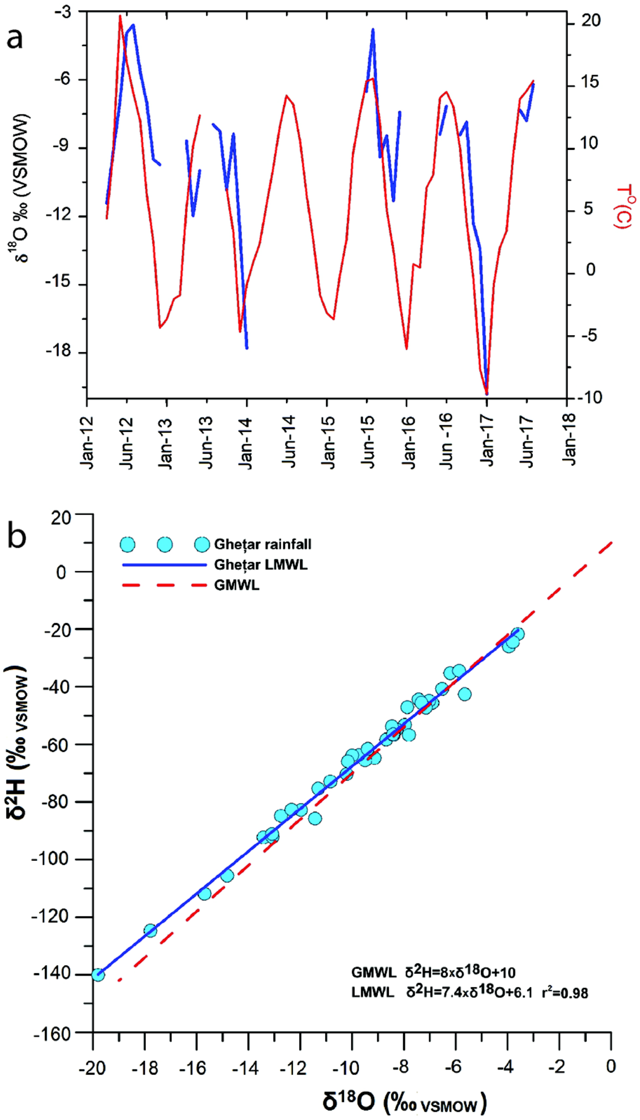


Figure 3. a) Temporal variability of $\delta^{18}O$ and $\delta^{2}H$ in precipitation and air temperature at Gheţar (10 km south of Focul Viu Ice Cave and at the same altitude), b) Local Meteoric Water Line of precipitation the same station, plotted against the Global Meteoric Water Line

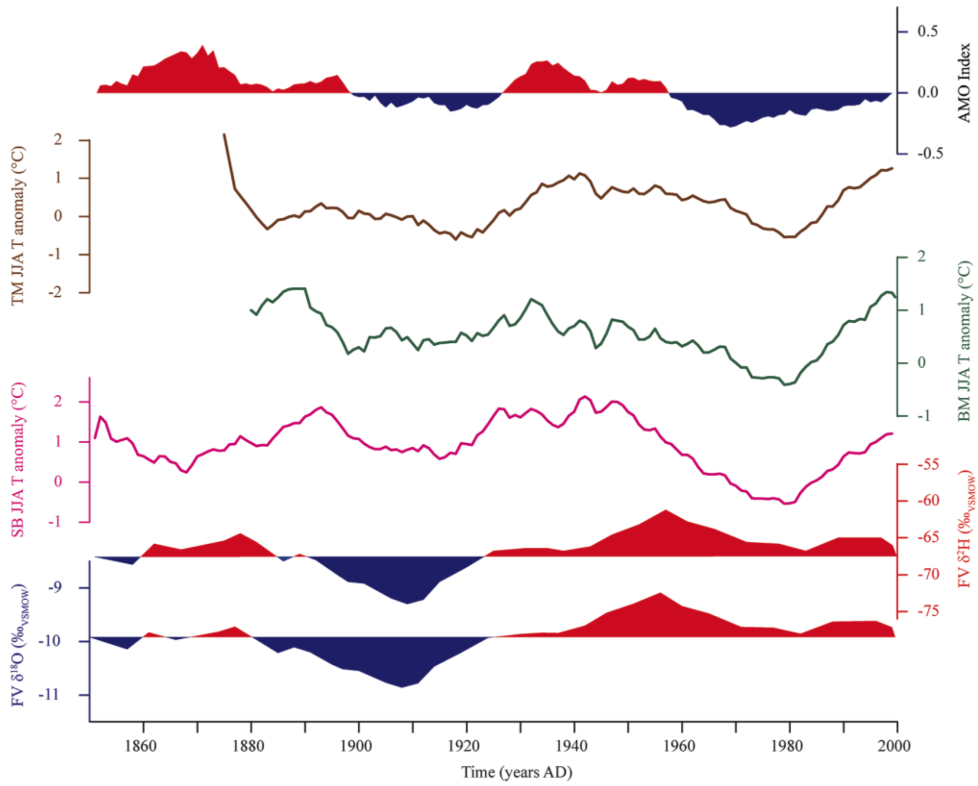


Figure 4. Temporal variability of the Atlantic Multidecadal Oscillation instrumental index, air temperature (anomalies with respect to the 1961-1990 period) recorded at Baia Mare (BM), Timișoara (TM) and Sibiu (SB) weather stations and FV $\delta^{18}O$ and $\delta^{2}H$ (‰) during the instrumental period.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

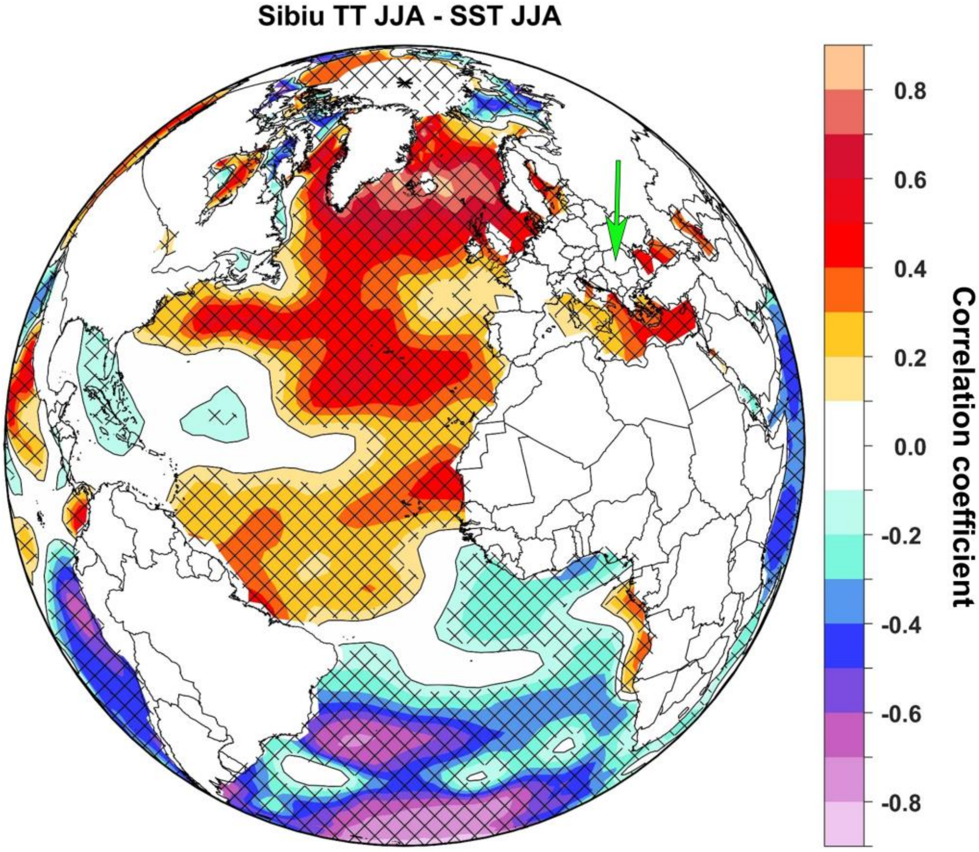


Figure 5. Spatial correlation map between Sea Surface Temperature (SST) and average summer (JJA June – July- August) air temperature at Sibiu (60 km south of Focul Viu Ice Cave, indicated by the green arrow) over the 1850-2011 period.

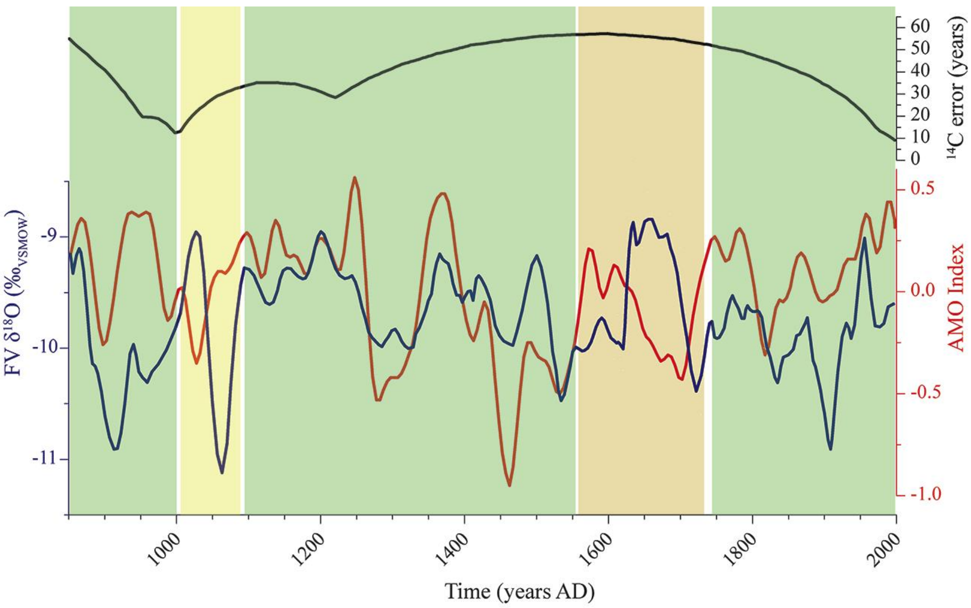
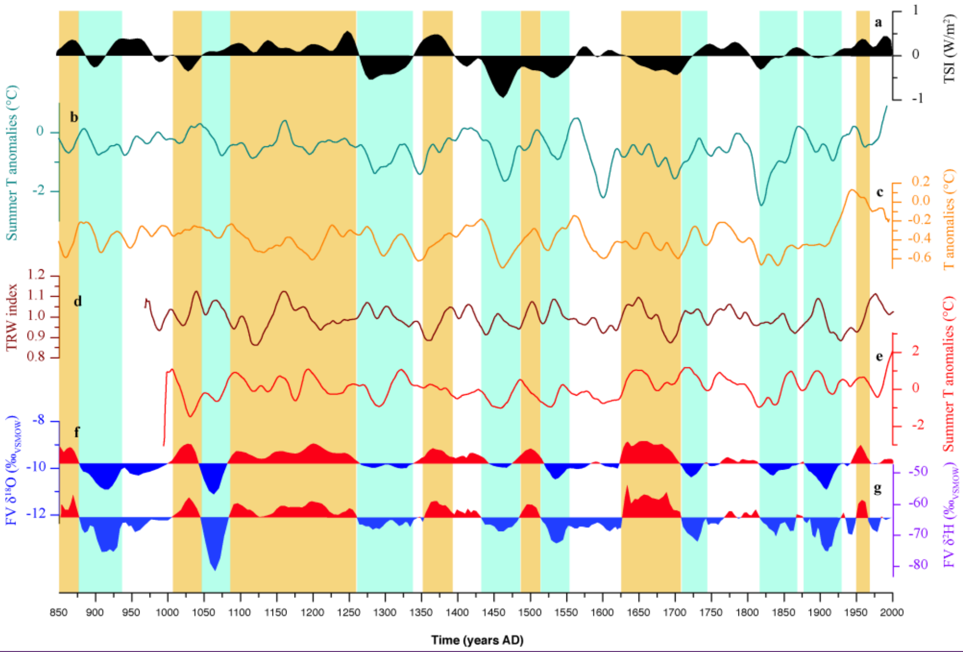


Figure 6. Temporal variability of the FV $\delta^{18}O$ (blue), the reconstructed AMO index (Wang et al., 2017) and the ^{14}C measurement uncertainty between AD 850 and 2000. Shading indicates the offset (in years) between the FV $\delta^{18}O$ and AMO index values: green – less than 20 years, yellow – between 20 and 50 years, orange – above 50 years.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TRW index
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FV δ¹⁸O (‰VSMOW)
FV δ²H (‰VSMOW)
Time (years AD)
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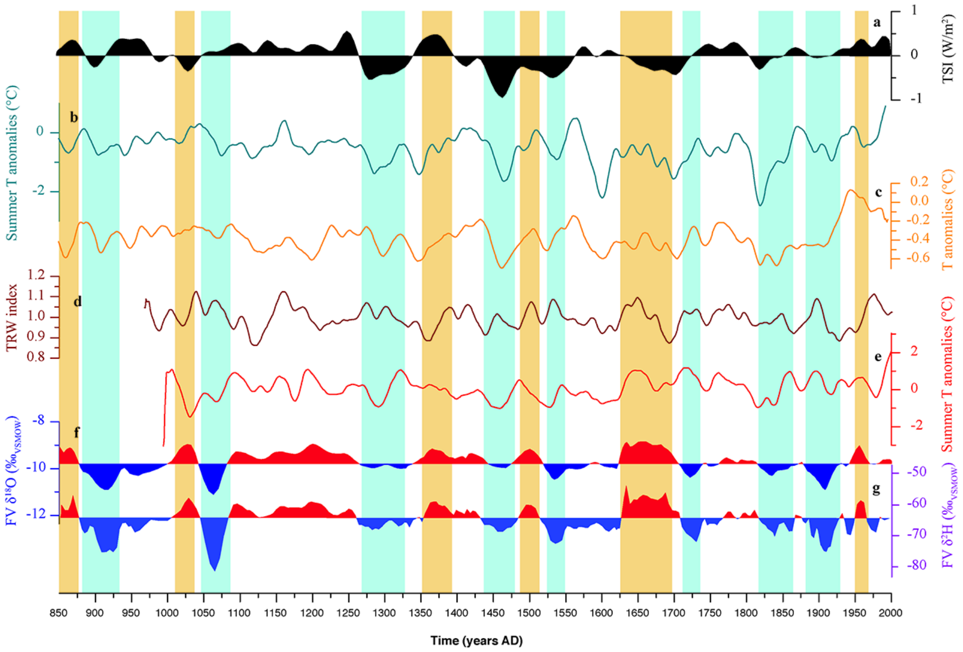
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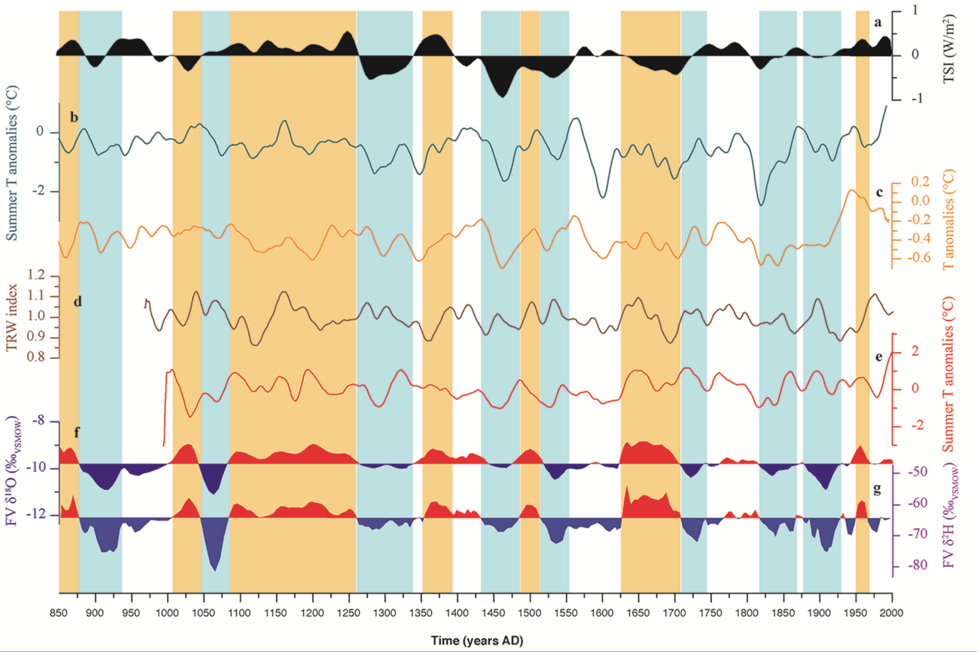

Figure 7. Summer climatic conditions recorded by $\delta^{18}O$ and $\delta^{2}H$ from FV ice core (panels f and g, bottom) and comparison with proxy indicator from the Northern Hemisphere: a) Total Solar Radiation (Steinhilber et al., 2009), b) Central Europe summer temperature anomalies (against the 1901-2000 mean, Buntgen et al., 2011); c) Northern Hemisphere air temperature anomalies (against the 1961-1990 mean, D'Arrigo et al., 2006), d) Tree Ring Width Index from Albania, SE Europe (Seim et al., 2012), 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.

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	1490±65

								805AD (2.6%) 845AD 860AD (91.5%) 1160AD	
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