

Brussels, Belgium, Sunday 15th March

Dear Prof. Fleitmann,

We thank you and the reviewers for the time and efforts you have devoted to our revised paper.

All comments of both reviewers were answered point by point and changes were incorporated in the manuscript. The manuscript was thoroughly reworked to a more coherent, shorter and more to point paper. The abstract, the introduction, study area and methods parts were shortened. The results and discussion parts were almost fully reworked with additional pictures and/or changes in pictures and tables such as demanded by the reviewers.

All changes in demanded by the reviewers are highlighted in blue. Since the parts results & discussion were fully reworked, we did not highlight the changes.

We hope that with these changes the manuscript can now be accepted for publication in *Climate of the Past*.

Kindest Regards,

Maite Van Rampelbergh
Sophie Verheyden
Mohammed Allan
Yves Quinif
Hai Cheng
Lawrence Edwards
Eddy Keppens
Philippe Claeys

Anonymous Referee #1

Received and published: 25 November 2014

Review of the manuscript "A 500 year seasonally resolved d18O and d13C, layer thickness and calcite fabric record from a speleothem deposited in equilibrium of the Han-sur-Lesse cave, Belgium" by Van Rampelbergh et al., submitted to *Climate of the Past*

General comment:

This is an interesting paper aiming to reconstruct past climate variability during the last ca. 500 years from a seasonally layered, exceptionally fast growing stalagmite from a cave in Belgium. The authors have already published a detailed study of the proxies and the underlying processes based on a cave monitoring program. Thus, the interpretation of the proxy data is relatively robust. The chronology is based on both counting of annual layers and U-Th-dating and, thus, also relatively robust. In summary, the paper is well written, and deserves publication in *Climate of the Past*.

However, one aspect is completely omitted: The potential occurrence of hiatuses. The authors report one major hiatus between 1810 and 1860, which is clearly documented by straw pieces embedded into the calcite. However, at least some of the described “anomalies” in the proxy records (Fig. 5), which display large and very abrupt changes in both $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ as well as in growth rate, show the typical signature of a hiatus, which is subsequently followed by a new onset of speleothem growth. Considering the relatively large uncertainties of the U-Th dating chronology (Table 2), hiatuses and – as a consequence – missing layers may not be detected from comparison of the U-Th and the lamina counting chronologies. This aspect needs to be discussed. Maybe the authors can use petrographic evidence to demonstrate (or exclude) the occurrence of hiatuses in their records.

The Proserpine stalagmite is a rapidly growing stalagmite with a clear layering in the upper ca. 56 cm we studied. It was demonstrated, based on comparison between U/Th dating and layer counting that one layer couplet is deposited per year (even if two parts, IV and VI, suggest possible problems of opening or contamination of the system by modern drip water). Moreover, some of us (Van Rampelbergh et al., 2014) studied the seasonal isotopic functioning of the vadose zone and the seasonal calcite deposition. The deposition dynamics in the Proserpine stalagmite is therefore well understood. The layer counting provides results that are very close to the expected period based on U-series data. It is therefore highly improbable that even minor hiatuses exist in the period studied in the speleothem. Especially because the Proserpine stalagmite currently fed throughout the whole year by a ‘real shower’ from many different drip sites, leading to a growth rate of the order of 1 mm per year. The ‘hiatus’ observed around 1850 is not due to non-deposition of calcite but is rather a perturbation due to the insertion of straw pieces in the calcite by humans. This most probably happened in a period of strongly decreased drip rate since there are strong indications that a fire has been lit on the stalagmite (Verheyden et al, 2006), which is impossible nowadays due to the dense dripping. The isotopic signatures with rapid and important $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ are therefore linked to changes in terms of more or less close to isotopic equilibrium, and consequently to changes in climatic conditions that are at least regional.

Furthermore, the authors discuss the changes in the stable isotope signals and layer thickness throughout the paper in terms of colder/drier vs. warmer/wetter winters. However, the same proxy signals could also result from a re-routing in the karst aquifer (resulting in increased PCP, lower drip rates, etc.). This is a general problem of all speleothem based palaeoclimate records, but since they do not present another, coeval record from the same cave showing the same variability in the proxy signals (reproduction!), such effects cannot be excluded for the presented record. This may particularly be the case for the anomalies. This aspect should at least be mentioned in the discussion of the proxy data. In this context, is there any evidence for anthropogenic influence above the cave (e.g., agriculture), potentially affecting recharge conditions during the last 500 years?

That some proxy-signals can change related to the routing of the water used through the vadose zone is certainly a crucial point as highlighted by the reviewer. This is certainly the case for elemental composition which is very

spatially dependent in caves and was studied in Han-sur-Lesse caves (cfr Verheyden et al, 2008: Verheyden S., Genty D., Deflandre G., Quinif Y. and Keppens E., 2008. Monitoring climatological, hydrological and geochemical parameters in the Père Noël cave (Belgium): Implication for the interpretation of speleothem isotopic and geochemical time-series. *International Journal of Speleology*, 37(3): 221-234.) This can be the case for $\delta^{13}\text{C}$. Depending on the routing, the effect of Prior Calcite Precipitation (PCP) can be less or more important, which can change the $\delta^{13}\text{C}$ of the carbonate ions due to repeated degassing of the water during the PCP process. However, as explained in chapter 5.2, this is not the case for the $\delta^{18}\text{O}$ of the vadose water, which has been studied in the Han-sur-Lesse cave (cfr Verheyden et al 2008; Van Rampelbergh et al., 2014) and which does not display spatial variation of more than 0.5 permil, which corresponds to the largest seasonal changes observed in the calcite $\delta^{18}\text{O}$. This means that the rapid and large $\delta^{18}\text{O}$ changes are changes related to real changes of overall conditions in the cave (which may be possibly linked to regional changes). It suggests the possible existence of threshold conditions inducing rapid and important change in isotopic composition due to changes in isotopic equilibrium status, linked to changing conditions and/or temperature changes (as explained in 5.5.).

Similarly, they should discuss the effects of water residence time in the karst aquifer and the related effect of smoothing on the drip water $\delta^{18}\text{O}$ signals. Even if the (analytical) resolution of the stable isotope data may be seasonal, the $\delta^{18}\text{O}$ signal may reflect a mixture of several years or even decades (Genty et al., 2014). This aspect is crucial for the interpretation of the stable isotope data and needs to be discussed.

Van Rampelbergh et al., 2014 largely discussed the smoothing effect of the vadose zone on the $\delta^{18}\text{O}$ composition of the drip waters in the Han-sur-Lesse cave. They demonstrated that the $\delta^{18}\text{O}$ and δD of the dripwater display almost no variation throughout the year, indicating that the residence time is sufficiently long to homogenize its isotopic composition. The change in isotopic signal can therefore not be due to seasonal variations or to rain or snow events. Moreover, the fact that the $\delta^{13}\text{C}$ changes at the same time as the $\delta^{18}\text{O}$ suggests a change due to other factors than a change in vadose water $\delta^{18}\text{O}$. Therefore a discussion on the mixture of one or several years of the vadose water is not crucial in deciphering the specific problem of important rapid changes. It is crucial however in the discussion of the longer-term trends.

Finally, some of the data/interpretations (e.g., correlations, seasonality) should be illustrated rather than just mentioned in the text. See my corresponding detailed comments below.

Detailed comments:

Title: I would delete "deposited in equilibrium" from the Title. Firstly, this is not the case for the whole record. Secondly, this very specific information makes the title quite long.

We thank the reviewer for this suggestion. The title of the manuscript was adapted to *"A 500-year seasonally resolved $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, layer thickness and calcite aspect record from a speleothem deposited in the Han-sur-Lesse cave, Belgium."*

Title and throughout the paper: I am puzzled by the use of the term "fabric". To my knowledge, this has been mainly used to describe crystallographic features in speleothems (e.g., columnar fabrics, compare for instance Frisia et al., 2000). In the

paper, the authors only differentiate between darker and whiter as well as more compact and more porous calcite. Thus, I would either delete the term "fabric" or present more detailed (microscopic) data.

We agree that the term "fabric" is not the best-suited term to use for describing the difference between darker and whiter as well as more compact and more porous calcite. A better term can be the calcite "aspect". The term fabric was adapted throughout the manuscript with the term calcite *aspect*.

Abstract: The abstract appears very detailed and relatively long to me. I would focus

on the most robust findings here, which would make the abstract much more concise.

Abstract was shortened to make it more concise.

p. 4151, lines 14-15: I suggest to remove isotope slang ("heavy", "light") throughout

the paper and use more positive/negative delta values.

We thank the referee for this suggestion and adapted the manuscript by replace the isotope slang terms with more positive/more negative throughout the manuscript.

p. 4152, line 25 ff.: Do the referenced records have a particularly high resolution?

With this sentence the authors illustrate that speleothems successfully can be used to reconstruct climate in Europe. Since the focus of this sentence is not the resolution of the climate record, but rather the success of the used archive, the sentence was adapted to: *"Speleothems have already often proven to enable climate reconstruction in Europe (Genty et al., 2003; Baker et al., 2011; McDermott et al., 2011; Fohlmeister et al., 2012; Verheyden et al., 2014).*

p. 4154, line 7 ff.: Perhaps the authors should mention other annually laminated speleothem records here (e.g., Boch et al., 2009; Scholz et al., 2012).

We thank the referee for this suggestion and added the two proposed papers in the reference list.

p. 4153, line 22 ff.: I suggest to move this detailed paragraph presenting previous work on the Proserpine stalagmite to the material and methods sections.

We think it is the best option to keep 'this detailed paragraph presenting previous work on the Proserpine stalagmite' in the Introduction, also in the new thoroughly reworked manuscript because many of the findings in our previous work, especially Verheyden et al 2008 and Van Rampelbergh et al., 2014, are

essential in our reaserch approach of the presented study, to which we were also strongly motivated by the previous work we refer to.

p. 4157, line 17 ff.: The layering is almost impossible to see in the current figures. I suggest to include an additional figure showing high-resolution pictures of specific sections of the speleothem illustrating the layering, changes in thickness, the sequence of dark and bright layers etc.

Such a figure was already made and published in the paper of Van Rampelbergh et al. 2014 “ Monitoring of a fast-growing speleothem site from the Han-sur-Lesse cave, Belgium, indicates equilibrium deposition of the seasonal $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals in the calcite. (COTP). To inform the reader that such picture was already published in a previous study we added the following sentence at the end of section 4.: *“Sampling for the stable isotopes was done layer per layer in the parts II to VII and reflects seasonal variations in the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals (for a high-resolution picture of the seasonally resolved isotope records, the authors refer to Fig. 4 in Van Rampelbergh et al., 2014).”*

p. 4158, line 7 ff.: I do not see any data marked in light grey in Table 1. We thank the referee for pointing this out and will make sure that the color contrast will be preserved when uploading the paper in the COTP website.

Table 1: In some cases, the corrected age is older than the uncorrected age. This cannot be the case. Please explain/clarify! Why are some ages bold?

The U/Th ages marked in light grey (numbers, 1,2,7,8,15,17,18 and 19) were measured by Verheyden et al. in 2001. When we correct these ages to be reported before 2013 we have to add 12 years to the corrected results obtained by Verheyden et al. This causes the U/Th ages with numbers 15,17,18 and 19 to have slightly higher corrected ages compared to the uncorrected age.

The bold ages must be errors that have occurred during uploading of the file. They have no function and the authors will make sure that these bolds are removed in the published version.

p. 4158, line 10 ff.: Actually, the speleothem does not contain large amounts of detrital Th (less than a ppb for almost all ages). However, the uppermost samples are very young and, thus, contain only very low amounts of radiogenic ^{230}Th . Please clarify.

We thank the referee for this comment and fully agree that the low amounts of ^{230}Th are responsible for the large uncertainties rather than the amounts of detrital Th. However, to make the whole manuscript more coherent, the Results part was rewritten. This sentence is not mentioned anymore in the manuscript.

Table 2: Please report uncertainties for the calculated growth rates (both based on U-Th-dating and layer counting).

We thank the referee for this suggestion and added the uncertainties for the growth rates in Table 2.

Section 4.2: I would like to see the U-Th-ages and the layer counting chronology in a diagram of age vs. depth. The StalAge age model could also be included in

this diagram. This would make it much easier for the reader to understand the construction of the chronology.

As suggested by the referee we added an Age-Depth figure with the U/Th ages. See Figure 4. We did not choose to introduce the results of the StalAge model since this is not the model that was used to determine the final age-depth relation of the Proserpine.

p. 4158, line 26 ff.: The discussion of the correlations would strongly benefit from a calculation of the running correlation between d18O and d13C. If a proper size of the window (e.g., 50 years) was used, this could nicely illustrate different parts of the record. This should be included in Fig. 3.

The point the authors want to emphasize in the manuscript is that the d13C and d18O signals display similar trends above the perturbation. Below the perturbation the d13C and d18O are most probably affected by different factors and display a different evolution. Doing a running correlation between these two variables does not clearly indicate this difference since the correlation will be established by looking at the correlation between the two variables point by point.

A better way is to report this difference is to calculate the Spearman's rank correlation coefficient or Spearman's rho. This is a nonparametric measure of the statistical dependence between two variables. It assesses how well the relationship between two variables can be described using a monotonic function, i.e. which is not necessarily linear. In the new version of the manuscript the difference in correlation between the part above the perturbation and the part below the perturbation are reported by the Spearman's rank correlation coefficient.

p. 4159, line 11 ff.: As mentioned above, the "very clear seasonal variations" are not visible in Fig. 3. Please include a high-resolution picture showing the seasonal nature of the laminae. Furthermore, I strongly suggest to plot the seasonality in the stable isotope signals rather than just mentioning it in the text. Following your reasoning, this quantity has been calculated and is available. It would be very illustrative if this was included in Figs. 3, 4 and 5.

For a clear picture of the seasonal laminae, the authors prefer to refer to Fig. 4 in the previous published manuscript of Van Rampelbergh et al. 2014 since this paper discusses the seasonal character of the layering and the seasonality in the resolved isotope signals.

Since we agree that the discussion of the seasonality (=section 5.6) was missing a clear Graph illustrating the seasonal amplitude we added figure 6 to the manuscript. In this figure, the reader can clearly see that the part below the perturbation was seasonally resolved and that the amplitude of the seasonality changes throughout the different colder and warmer periods of the LIA.

p. 4160, line 27 ff.: "...the good agreement between the changes in growth rates suggested by the layer counting model and the changes in growth rate indicated by the layer thickness measurements suggests that the layer counting age model is the most accurate." This appears as circular reasoning to me since both quantities are based on the counting of annual layers.

We thank the reviewer to draw our attention to this point, which may indeed not

be clear. This approach may indeed appear as circular reasoning, but we are convinced that it is not. In the discussion on the relations between apparent U/Th-ages, number of counted layers, growth rates, thickness of layers, lengths and duration of sections, numbers of years etc., all with their analytical and/or statistical uncertainties, and that are all functions of 'time' being the unknown, we do start our analysis with the '*a priori*' assumption that , all layer duplets, consisting of a lighter and a darker one, correspond to one year, which is an observation that some of us (Van Rampelbergh et al., 2014) have demonstrated in a careful well documented monitoring study of the section covering the youngest 10 years of the same drill core. Without this observation all reasoning related to the unknown time would indeed be circular. In order to clarify this concept to the reader we briefly explain it in the text.

p. 4162, line 7 ff.: As mentioned in my general comment, it appears to me that some of the "anomalies" could reflect hiatuses. Please include this hypothesis in the discussion, in particular since the U-Th-chronology is not precise enough to exclude the presence of missing laminae (hiatuses).

See our discussion on possible hiatuses in the '**general comment**'

p. 4162, line 13 ff.: Please provide the (running) correlation between the stable isotope signals and lamina thickness. It is hard to see the correlations only based on the figures. A running correlation would be particularly useful to identify temporal changes in the correlation between the individual proxies.

The main message in comparing the isotope values with the layer thickness values is that when isotope values (and mostly the d180 values) are more negative, the layer thickness increases. A (running) correlation analysis is not necessary to illustrate this relation. However, we agree that if the term 'correlation' is used to describe the similar trends, such a s was done in the submitted version, the reader expects results of a (running) correlation analysis. Since a correlation analysis is not necessary to indicate that more negative d180 values correspond with thicker layers, the term 'correlation' was removed from this discussion.

p. 4162, line 27 ff.: Please provide the temporal evolution of the seasonality of the stable isotope signals in a plot. It is impossible to deduce this from the current figures.

The temporal resolution of the isotopes is not fixed from the part above the perturbation since the sampling was done at fixed distances (every 1mm). Only below the perturbation (part between 1810 and 1479 AD) samples were drilled in every layer and are thus always seasonally resolved. Since this difference was not clear in the first version of the manuscript, the text has been re-written to better illustrate this difference. However, we do not think that adding a plot explaining this is necessary in the manuscript.

p. 4163, line 7 ff.: Changes in speleothem d180 values may also result from changes in seasonality as the authors themselves point out. This should be included.

We think that this is better explained in the new version of the manuscript.

p. 4163, line 26: The paper from Baldini et al. (2002) has been retracted. Please remove the corresponding reference.

The discussion of 5.3 The possible factors driving the d18O and d13C values layer thickness and calcite fabric was thoroughly rewritten to make a smoother text and this sentence was removed from the manuscript.

p. 4163, line 27 ff.: The effect of the residence of the water in the karst aquifer on the d18O values of the drip water and speleothem calcite is completely omitted from the discussion. Perhaps this has been discussed in the monitoring paper, but since this point is crucial for the interpretation – at least on the seasonal to annual scale – this must be included here. In a recent paper, Genty et al. (2014) have shown that the residence time may have a large effect of drip water d18O values. This aspect should be discussed.

We think that this point is better explained in the new version of the manuscript.

p. 4164, line 16 ff.: I agree that the majority of the recharge water originates from winter and that summer rainfall probably contributes less. However, Genty et al. (2014) have impressively shown that summer rainfall may still have a substantial effect on the d18O value of cave drip water. Since the basic assumption for the interpretation of the stable isotope records is that the recharge water mainly reflects winter precipitation, this is a crucial point and should be critically discussed. Please expand the discussion on this and also on smoothing effects due to mixing in the karst aquifer (see above).

We think that this point is better explained in the new version of the manuscript.

p. 4165, line 4 ff.: One aspect I am missing in the discussion of the d13C values is the effect of host rock dissolution occurring in the closed/open system. This may have a large effect on the d13C values of the drip water both on short (annual) and longer (centennial) time-scales (see e.g., Fohlmeister et al., 2011). This should be included.

The open/closed system is a classical problem of the epikarst system, which is related to the varying impact of PCP. We think it is better explained in the new version of the manuscript, in which we refer to previous work by some of us (Verheyden et al., 2008) on the seasonal co-variation of Mg/Ca and Sr/Ca with changes in the effect of PCP, which is discussed in the new version of manuscript.

p. 4167, line 12 ff.: I am not sure that changes in soil productivity cannot occur on much shorter time-scales (i.e., decadal if not even shorter).

We think that this point is better explained in the new version of the manuscript.

p. 4167, line 28: Please show the correlation between colder and dryer winters in the instrumental data or at least present the correlation coefficient.

As suggested by the reviewer, the correlation coefficient between the winter temperature and the precipitation intensities measured by the RMI were added to the manuscript in section 5.2: “Furthermore, a good Spearman correlation can be established between lower winter precipitation intensities (DJF) and lower winter temperatures (DJF) measured by the RMI since 1833 ($\rho = 0.47$ and $p = 3.99 \times 10^{-11}$) suggesting that drier winters correspond to colder winters.”

p. 4168, line 2 ff.: I am not convinced that the large isotope excursions (the “anomalies”) are due to disequilibrium fractionation. I rather suspect that at least some of them are related to hiatuses (see above). Please present further evidence that this is not the case.

See our discussion on possible hiatuses in the ‘**general comment**’

p. 4168, line 22 ff.: I do not agree that the anomalies are related to “exceptionally cold and dry winters”. I rather think that these events are related to short-term hiatuses, which may also be related to re-routing in the karst aquifer. This possibility should at least be mentioned. The authors mention “non-climatic factors” below to explain some of the anomalies, but this discussion should be expanded.

See our discussion on possible hiatuses in the ‘**general comment**’

p. 4170, line 26 ff.: “This observation corresponds with colder conditions in Europe (Fig. 5h–j) (Van Engelen et al., 2001; Le Roy Ladurie, 2004; Luterbacher et al., 2004; Dobrovolny et al., 2010) and confirms, that although calcite is white matter, the isotopes still record climate variations.” I do not agree with this statement. It is encouraging that the other reconstructions also show colder conditions for the corresponding periods. However, the duration and shape of the cold phases is very different. The duration is much shorter in the other reconstructions. Furthermore, the speleothem record suggests a progressive cooling during the interval, which is not visible in the other records. This statement is thus associated with large uncertainty. I would rephrase the whole paragraph and definitely not use “confirm”.

We think that this point is better explained in the new version of the manuscript.

p. 4170, line 5 ff.: This interpretation seems OK to me, but I would again mention the possibility that the anomalies are related to non-climatic or even anthropogenic factors.

We think that this point is better explained in the new version of the manuscript.

Section 5.6: This paragraph only makes sense if seasonality is plotted and included in

the figures. As these data seem to be available, it should be no problem to plot them.

This would allow the reader to follow the reasoning much more easily.

We fully agree with this comment and added a plot of the discussed data in Figure 6.

p. 4176, line 24 ff.: The “speleothem data from the Alps” are mentioned (without a reference) for the first time here. Please provide a reference and include the corresponding data in the discussion and in the figures.

The discussion part of the manuscript was thoroughly rewritten and the comparison with the Alpine record was removed.

p. 4177, line 1 ff.: This section should only be included if seasonality is plotted and compared with the other proxies (see my comment above).

Figure 6, illustrating the seasonal evolution of the $\delta^{18}O$ and $\delta^{13}C$ signals was

added to section 5.5. *Seasonality in d18O and d13C values*. Therefore conclusion point number 5 was kept in the manuscript.

Anonymous Referee #2

General Comments: This is an interesting and quite detailed study of a 500 year seasonally resolved speleothem stable isotope record from Han-sur-Lesse cave, Belgium. My general impression is that the authors have completed a careful multi-proxy study and for the most part have matched their careful analytical work with thoughtful and well considered and supported interpretations. The U-series data are clearly problematic and I think that even less discussion should be given over to these data. It is finally stated near the top of page 4161 that the layer counting model is used to establish the chronology for the stalagmite; perhaps convey this information to the reader earlier in this section. My other main concern is that the manuscript is currently too long (c.50 pages) and I would strongly recommend that the authors try to reduce the overall length of the text, paying particular attention to possible repetition in places. A more concise text will improve the readability of the manuscript and ultimately will improve the impact of the work.

In the interpretation/discussion section, changes in the NAO state are often invoked to explain the periods of anomalously high d18O values (cold-dry periods. These are often linked to negative NAO periods in the reconstruction of Trouet et al. (2009). I would like to see the Trouet et al. curve plotted on the same diagrams (e.g. Figs. 4 and 5) so that the reader can more easily assess these putative links. It should also be noted that negative NAO conditions are known to be associated with more easterly-derived moisture that typically has more lower d18O values (e.g. Baldini et al., 2008, *Geophys. Res. Lett.* 35, GL032027 and Baldini et al. (2010) *Climate Dynamics* 35, 977-993). The point is that negative NAO conditions would be expected to produce lower rainfall d18O. One would then have to argue that this effect is overwhelmed by the non-equilibrium effects that apparently give rise to higher d18O and d13C in the Prosperine stalagmite during these periods. I do not wish to claim that the authors' interpretation of a link to the NAO is incorrect, but the magnitude of the non-equilibrium effects on d18O and d13C would have to be quite large to produce the observed 'anomalies' (high values) if rainfall values for d18O were lower than usual. Are there any particular ventilation effects that might make the cave particularly sensitive to NAO conditions (wind directions etc.)?

The authors fully agree that the general length of the manuscript was too long. Therefore different parts of the text were re-written and made more concise. This was done for the Abstract, part 2. Study Area, part 4. Results and part 5. Discussion.

In the submitted manuscript the d18O variations were suggested to be linked with variations of the NAO with more positive d18O values reflecting colder and drier periods. However, we agree that this link is somehow difficult to establish. Therefore the discussion has been re-written in the reviewed manuscript. The focus is not put more on the similarities between our the climatic interpretation

of the Proserpine records and the findings in climate reconstructions mostly based on historical archives such as the studies of Le Roy Ladurie 2004, Luterbacher et al., 2004, Dobrovolny et al., 2010. The link with the NAO is discussed more carefully at the end of section 5.3 Anomalies in the proxy records.

Given the absence of Mg/Ca and Sr/Ca data I think the authors should steer clear of making interpretations that include statements about prior calcite precipitation. In the absence of the trace element data, such interpretations are probably overly speculative.

Given the absence of Mg/Ca and Sr/Ca data' indeed, we present a study that does contain many other data, leading to interpretations that are the most plausible in our opinion, including the occurrence of prior calcite precipitation (PCP). The latter is indeed not supported by Mg/Ca and Sr/Ca data, because we don't have them. This absence of Mg/Ca and Sr/Ca data is however not a reason to a priori disregard the occurrence of prior calcite precipitation, as a possibly valuable explanation for certain observations based on several other data.

Moreover, this interpretation is based on the observations made by some of us (Verheyden et al., 2014), and referred to in the Introduction, in a speleothem in the Père Noël cave, which is part of the same Han-sur-Lesse cave system, in which the similarly varying isotopic ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) and geochemical (Mg/Ca and Sr/Ca) proxies could be interpreted in terms of alternations of wetter and drier phases, causing changes between weaker or absent PCP and more intense PCP respectively. We added this argument to '**5.2 Factors driving decadal and multi-decadal changes in the measured proxies** in the text' of the new version of the manuscript.

Mg/Ca and Sr/Ca- analyses would be among the first things to be done to verify certain of our interpretations.

In Table 1, the $^{230}\text{Th}/^{232}\text{Th}$ ratios should be given as activity ratios, not atomic ratios. Most readers will be able to tell at a glance that many of these samples are contaminated by detrital thorium if these ratios are given as activity ratios (e.g. is the activity ratio < 100 etc). As presented in Table 1, these numbers are difficult to convert to activity ratios unless the reader happens to have a calculator to hand and he/she happens to know the ratio of the decay constants of ^{230}Th and ^{232}Th . Help the reader – convert these ratios to activity ratios.

The U/Th-ages are given as they are usually presented with their uncertainties and taking into account the possible contamination by detrital thorium. We think that the robustness of the age model we use is mainly in the careful combination of the two independent methods: layer counting and sufficient U/Th (20 in 56 cm or ca. 500 years), using StalAge.

Specific Comments and minor corrections:

Abstract: The abstract is informative but is overly detailed and too long for an abstract. The purpose of the abstract is to convey the major findings of the study in a concise manner to the reader. Details of how the interpretations are supported can be omitted and discussed within the text of the manuscript itself. There are also a few typographical errors (e.g. upper case A is missing at the beginning of two sentences).

We agree with this comment and reduced the length of the abstract.

P. 4153, line 5: 'To allow reconstruction of' instead of 'To allow reconstructing'-
Adapted.

P. 4154, line 3: 'in more detail', not 'more in detail'- Adapted.

P. 4156, line 19: I suggest you use 'number of counted layer couplets' rather than
'amount of counted layer couplets'- Adapted.

P. 4158, line 12: 'number of years' rather than 'amount of years'- Adapted.

Similar comment on P. 4159, line 24.- Adapted.

P. 4163, lines 14 and 15: The 'amount effect' causes $\delta^{18}O$ values to decrease
during

wetter periods, i.e. become more negative, (not increase as stated here).

We agree with the reviewer that this sentence was not correct. However, to
shorten the length of the manuscript, the discussion part was thoroughly
rewritten and this sentence was removed from the manuscript.

P. 4163, line 27: 'smaller scale' not 'smaller scale'.- To shorten the length of the
manuscript, the discussion part was thoroughly rewritten and this sentence was
removed from the manuscript.

P. 4164, line 10: 'assuming' would be better than 'considering'. This is definitely
an

assumption. To shorten the length of the manuscript, the discussion part was
thoroughly rewritten and this sentence was removed from the manuscript.

P. 4165, line 4: 'large scale', not 'large scaled'. To shorten the length of the
manuscript, the discussion part was thoroughly rewritten and this sentence was
removed from the manuscript.

P. 4171, line 8: The possibility of a lit fire on the Prosperine stalagmite does
indeed

suggest dry conditions, but they may have been short-lived, perhaps a season or
two? I'm not convinced that this is necessarily evidence for drier conditions on
decadal timescales, as implied here.

The physical evidence that supports the presence of a lit fire on the Prosperine
stalagmite in the past doesn't indeed suggest more than dry conditions for a
short period of time, e.g. 'perhaps a season or two' at least. Apart from a
maximum duration, that cannot have been longer than the estimated duration of
the hiatus, we have no evidence for its duration neither for its continuous
character. Therefore it cannot be used to support the duration of the drier
conditions indeed. But the occurrence of the drier period, and its duration of
decadal order, is derived from the stable isotope record. We only refer to the
physical evidence of the presence of a lit fire, 'at some time' during this drier
period, because it demonstrates that at least during a certain part within this
period of time, the conditions on top of the stalagmite cannot have been too wet
to lit a fire, as they are today, and most probably have been throughout the
whole formation of the speleothem taking into account the generally high growth
rate.

P. 4174, line 22: 'measured' not 'measure'- Adapted.

1 **A 500-year seasonally resolved $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$, layer thickness and calcite**
2 **aspect record from a speleothem deposited in the Han-sur-Lesse cave,**
3 **Belgium.**

4
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21
22 **Abstract**

23 Speleothem $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals enable climate reconstructions at high
24 resolution. However, scarce decadal and seasonally resolved speleothem records
25 are often difficult to interpret in terms of climate due to the multitude of factors
26 that affect the proxy signals. In this paper, a fast growing (up to 2 mm/y)
27 seasonally laminated speleothem from the Han-sur-Lesse cave (Belgium) is
28 analyzed for its $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, layer thickness and changes in calcite
29 aspect. The studied record covers the period between 2001 and 1479 AD as
30 indicated by layer counting and confirmed by 20 U/Th-ages. The Proserpine
31 proxies are seasonally biased and document drier (and colder) winters on multi-
32 decadal scales. Higher $\delta^{13}\text{C}$ signals reflect increased prior calcite precipitation
33 (PCP) and lower soil activity during drier (and colder) winters. Thinner layers
34 and darker calcite relate to slower growth and exist during drier (and colder)
35 winter periods. Exceptionally dry (and cold) winter periods occur from 1565 to
36 1610, at 1730, from 1770 to 1800, from 1810 to 1860 and from 1880 to 1895
37 and correspond with exceptionally cold periods in historical and instrumental
38 records as well as European winter temperature reconstructions. More relative
39 climate variations, during which the four measured proxies vary independently
40 and display lower amplitude variations, occur between 1479 and 1565, between
41 1610 and 1730 and between 1730 and 1770. The winters during the first and
42 last periods are interpreted as relatively wetter (and warmer) and correspond
43 with warmer periods in historical data and in winter temperature
44 reconstructions in Europe. The winters in the period between 1610 and 1730
45 are interpreted as relatively drier (and cooler) and correspond with generally
46 colder conditions in Europe. Interpretation of the seasonal variations in $\delta^{18}\text{O}$ and
47 $\delta^{13}\text{C}$ signals differs from that on decadal and multi-decadal scale. Seasonal $\delta^{18}\text{O}$
48 variations reflect cave air temperature variations and suggest a 2.5 °C
49 seasonality in cave air temperature during the two relatively wetter (and

50 warmer) winter periods (1479-1565 and 1730-1770), which corresponds to the
51 cave air temperature seasonality observed today. Between 1610 and 1730, the
52 $\delta^{18}\text{O}$ values suggest a 1.5 °C seasonality in cave air temperature indicating colder
53 summer temperatures during this drier (and cooler) interval. The $\delta^{13}\text{C}$
54 seasonality is driven by PCP and suggests generally lower PCP seasonal effects
55 between 1479 and 1810, compared to today. A short interval of increased PCP-
56 seasonality occurs between 1600 and 1660, and reflects increased PCP in
57 summer due to decreased winter recharge.

58 59 **1. Introduction**

60
61 In the studied western European region, high-resolution climate records
62 covering the last 500 years are scarce. Most climate information at seasonal or
63 yearly scale is retrieved from historical data such as the price of flour or grapes
64 (Van Engelen et al., 2001; Le Roy Ladurie, 2004) which may induce biases in the
65 climate record. Therefore it is necessary to confront information from different
66 archives, based on different approaches.

67
68 Speleothems have already often proven to enable climate reconstruction in
69 Europe (Genty et al., 2003; Baker et al., 2011; McDermott et al., 2011;
70 Fohlmeister et al., 2012; Verheyden et al., 2014). On millennial and centennial
71 scales, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variations can often be related to a single climate proxy
72 such as temperature or vegetation cover (Spötl and Mangini, 2002; Genty et al.,
73 2003; McDermott, 2005). However, on decadal and seasonal scale, a larger range
74 of factors can influence the $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, layer thickness or calcite aspect of a
75 speleothem making an interpretation in terms of climate more difficult. To allow
76 reconstruction of the climate up to seasonal variation using mid-latitude
77 speleothems, a detailed analysis of each used proxy must be compared with a
78 multiproxy approach. Different European records have enabled to reconstruct
79 climate successfully by using this approach (e.g. Frisia et al., 2003; Niggemann et
80 al., 2003; Mangini et al., 2005; Matthey et al., 2008; Fohlmeister et al., 2012).

81
82 Belgian speleothems have the valuable advantage to often display a clear
83 internal layered structure reflecting seasonal variations (Genty and Quinif,
84 1996). The link between layer thickness and water excess in Belgian stalagmites
85 for the Late Glacial and Holocene period has clearly been demonstrated by Genty
86 and Quinif (1996). The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals from a speleothem sampled in the
87 Père Noël cave were interpreted as due to variations in cave humidity and drip
88 rate inducing changes in the kinetics of the calcite deposition occurring closer or
89 less close to isotopic equilibrium. More negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values occur
90 during periods of higher cave water recharge, when calcite deposition occurs
91 closer to isotopic equilibrium (Verheyden et al., 2008). In this speleothem, the
92 isotopic ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) and geochemical (Mg/Ca and Sr/Ca) proxies vary
93 similarly and record the climate in terms of wetter and drier phases (Verheyden
94 et al., 2014). The studied Proserpine stalagmite is a large tabular shaped
95 speleothem, growing in the Han-sur-Lesse cave, which is part of the same cave
96 system as the Père Noël cave. A former study of the stalagmite (Verheyden et al.,
97 2006) revealed deposition from 200 AD to 2001 AD, indicating an exceptionally
98 high average growth rate of ± 1 mm/y. The upper 56 cm, which covers the last

99 522 years is clearly layered. The similar variability of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals
100 and the layer thickness was linked to changes in effective precipitation (rainfall
101 minus evapo-transpiration). These proxies therefore have the potential to be
102 used to reconstruct climate in terms of wetter and drier phases.

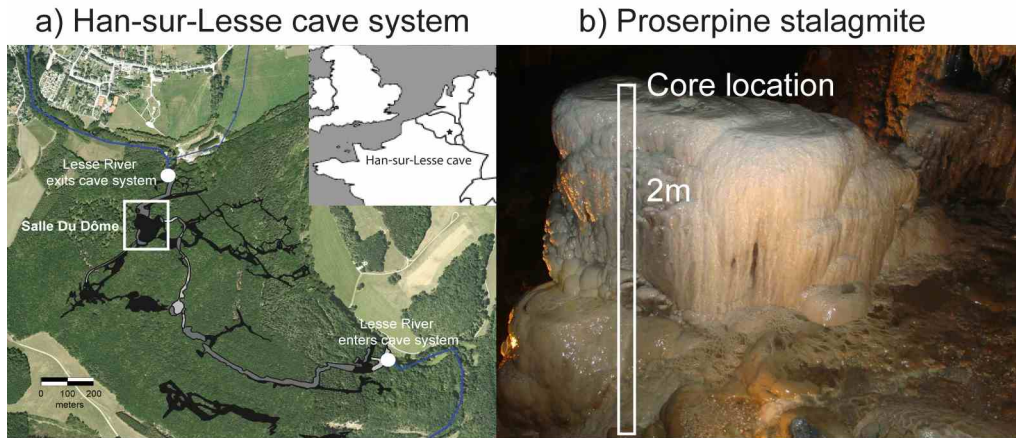
103
104 In this paper we study this potential [in more detail](#) and up to a seasonally
105 resolved timescale. An absolute age model is established by combining layer-
106 counting ages with measured U/Th-ages. A comparison of variations in layer
107 thickness, calcite aspect, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals in the light of former studies
108 (Genty and Quinif, 1996; Verheyden, 2001; Genty et al., 2003; Mühlinghaus et al.,
109 2007; Boch et al., 2009; Wackerbarth et al., 2010; Fohlmeister et al., 2012; Scholz
110 et al., 2012; Verheyden et al., 2014) and monitoring of the same stalagmite
111 location (Van Rampelbergh et al., 2014) leads to a better understanding of how
112 these proxies are related among them and how they reflect climate variations.
113 Comparing the Proserpine climate signal with winter temperature
114 reconstructions in Europe (Le Roy Ladurie, 2004; Luterbacher et al., 2004;
115 Dobrovolny et al., 2010) further verifies the proposed climate interpretation.

116 117 **2. Study area**

118
119 The Proserpine stalagmite is sampled in the Salle-du-Dôme chamber in the Han-
120 sur-Lesse cave, southern Belgium (Fig. 1). The Han-sur-Lesse cave is a meander
121 cutting of the Lesse-river, which still flows through the cave. The large rooms,
122 the multiple entrances and the presence of the river make it a well-ventilated
123 cave. Part of the cave, including the Salle-du-Dôme, is a show cave since the mid
124 19th century. The Salle-du-Dôme, being the largest chamber of the cave system
125 (150 m wide and 60 m high), is located under ca. 40 m of Givetian limestone
126 (Quinif, 1988) with a C3-type vegetation covered soil. The Proserpine stalagmite
127 is a 2 m high stalagmite with a large tabular shape (with a horizontal 70 cm by
128 150 cm to surface) that was actively growing when cored in 2001. A rain of
129 seepage water throughout the year feeds the stalagmite. Such fast growing ‘tam-
130 tam’ shaped stalagmites have the property to record climate signals and
131 environmental information at high resolution (Perette, 2000).

132
133 The mean annual precipitation at the meteorological station of Han-sur-Lesse is
134 844 mm/y and the mean annual air temperature averages 10.3°C (Royal
135 Meteorological Institute Belgium, hereafter named RMI) characterizing a warm
136 temperate, fully humid climate with cool summers (Kottek et al., 2006). While
137 the temperature displays a well-marked seasonality with cool summers and mild
138 winters, the rainfall is spread all over the entire year. The external seasonality in
139 temperature causes a subdued temperature variation within the Salle-du-Dôme
140 of 2 to 2.5 °C between summer and winter (Van Rampelbergh et al., 2014).
141 Present-day calcite is deposited in isotopic equilibrium with its drip water (Van
142 Rampelbergh et al., 2014). The $\delta^{18}\text{O}$ signal of freshly formed calcite collected on
143 top of the Proserpine varies seasonally due the changes in cave air temperature.
144 The $\delta^{13}\text{C}$ signal varies seasonally due to changes in prior calcite precipitation
145 (PCP) intensity, driven by changes in effective precipitation. At a seasonal scale
146 the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals display an opposite behavior with more negative $\delta^{18}\text{O}$

147 values in summer, when the $\delta^{13}\text{C}$ values are less negative (Van Rampelbergh et
148 al., 2014).
149



150
151 Figure 1 a) The Han-sur-Lesse cave system is located in the southern part of
152 Belgium. The Proserpine stalagmite was sampled in the Salle-du-Dôme chamber
153 (white square) located 500 m from the cave exit. b) The Proserpine stalagmite
154 with the location of the 2 m long core that was drilled in 2001 at the spot where
155 most of the drip water falls.

156 157 3. Methods

158
159 The Proserpine stalagmite was sampled in January 2001, by drilling a 2 m core,
160 10 cm wide, in the tabular shaped stalagmite. The precise location was on the
161 side with the highest drip rate but far enough away from the edge to avoid
162 disturbance of the expected horizontal layering of the growth increments (Fig.
163 1b). The core was cut in half and a slab of 1 cm was cut from the center. The slabs
164 were polished by hand with carbide powder and finished with Al_2O_3 . The upper
165 56 cm, was further studied and cut in seven parts, numbered I to VII (Fig. 2), to
166 allow easy handling in the laboratory. Layers were counted per part under the
167 Mercantec Micromill microscope and on high-resolution scans using Adobe
168 Illustrator. To increase the reliability of the layer counting, layers were counted
169 by different authors, on different days and with different zooms when counted
170 on computer screen. The reported layer amount is given by the average of 10
171 layer counting rounds per part. The thickness of each layer was measured using
172 the measurement tool of the Merchantec Micromill microscope with an
173 uncertainty of 0.1 μm . Samples for $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ measurements were taken with
174 a drill bit of 0.3 mm diameter mounted on a Merchantec Micromill. Ethanol was
175 used to clean the speleothem surface and drill bit prior to sampling. Between
176 samplings, drill bit and speleothem surface were cleaned with compressed air.
177 Samples were drilled every 0.5 mm in part I and in every layer for the other
178 parts, in total 867 samples. Stable isotope measurements were carried out using
179 a Kiel-III-device coupled on a Thermo Delta plus XL with analytical uncertainties
180 $\leq 0.12\text{‰}$ for $\delta^{13}\text{C}$ and $\leq 0.16\text{‰}$ for $\delta^{18}\text{O}$. A total of 20 U-series age, among which
181 8 from a former study (Verheyden et al., 2006) were measured at the University
182 of Minnesota (USA), using the procedures for uranium and thorium as described
183 in Edwards et al. (1987) and Cheng et al. (2000; 2009a; 2009b). StalAge (Scholz
184 and Hoffmann, 2011) was used to interpolate the ages between the U/Th-age

185 points. The seasonal character of the layering (Verheyden et al., 2006; Van
186 Rampelbergh et al., 2014) in the Proserpine allows using layer counting to
187 establish an age model. The number of counted layer couplets per part
188 represents the number of years for that part. The number of years obtained by
189 layer counting is then compared with the number of years suggested by the
190 U/Th-ages per part. Results of both independent dating methods are combined
191 to provide the final age model. The uncertainties (2σ) on all reported values
192 correspond with a 95% confidence interval and are calculated according to the
193 following relation:

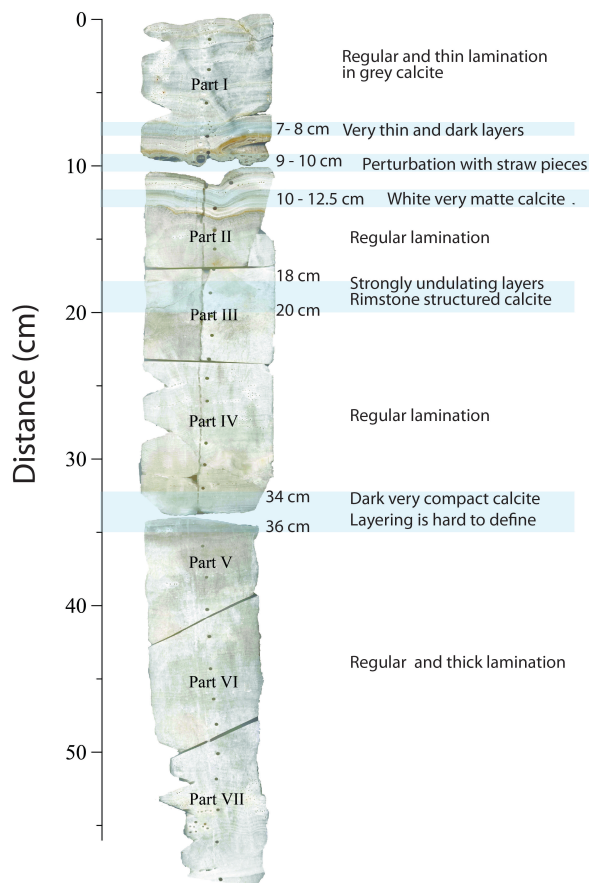
$$\bar{x} - t_{0.05,n-1} \cdot s/\sqrt{n} \leq \bar{x} \leq \bar{x} + t_{0.05,n-1} \cdot s/\sqrt{n}$$

196 where \bar{x} is the arithmetic mean of the results, n the number of replicates, t the
197 student distribution function and s the standard deviation on the results. If $n \geq$
198 30, t approximates a normal distribution and is roughly equal to 2.
199

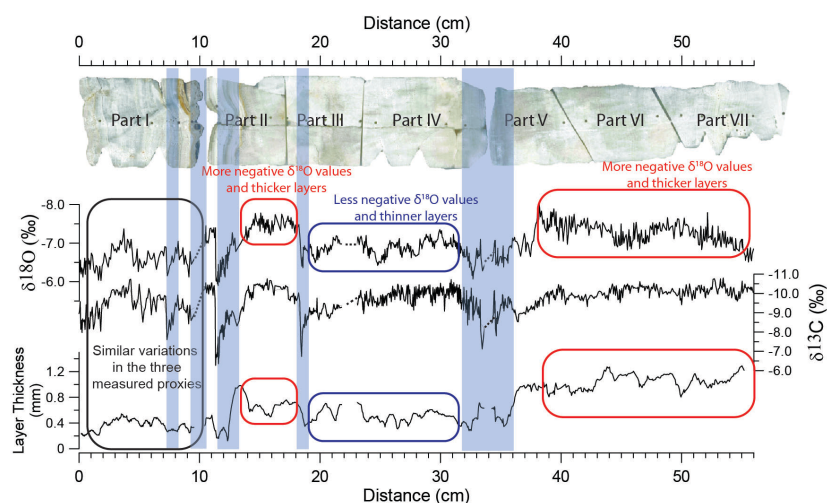
200 4. Results

201 Layering is present in the studied upper 56 cm of the Proserpine core and is
202 formed by alternating dark more compact and white more porous layers. The
203 seasonal character of the layering in the Proserpine stalagmite, with one dark
204 and one white layer deposited every year is suggested by Verheyden et al.
205 (2006) and further confirmed by monitoring results of the Proserpine growth
206 site (Van Rampelbergh et al., 2014). The Proserpine stalagmite displays a clear
207 sedimentological perturbation between 9 cm and 10 cm (Fig. 2). During this
208 perturbation, calcite deposition is heavily disturbed with straw pieces embedded
209 in the calcite, which might be relics from fires lit on the paleo-surface of the
210 stalagmite to illuminate the Salle-du-Dôme (Verheyden et al., 2006). Apart from
211 this sedimentological perturbation, no features were found that could be
212 interpreted as signs of interruptions ('hiatuses') of the continuous
213 sedimentation. Even though layering is less clearly visible in certain parts, due to
214 the calcite aspect, or where the sub-horizontal layering is strongly disturbed,
215 there were always parts across the 10 cm width of the slab where the continuity
216 of the layering was clearly visible throughout the full length of the core apart
217 from that perturbation between 9 and 10 cm. Four proxies were measured on
218 the Proserpine stalagmite: calcite aspect, layer thickness, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values.
219 Layer thickness varies between 0.05 and 1.7 mm/layer (Fig. 3) and dark layers
220 are on average 0.05 mm thinner than white layers. The $\delta^{18}\text{O}$ values average -6.9
221 ± 0.16 ‰ and the $\delta^{13}\text{C}$ values average -10 ± 0.12 ‰. Four intervals
222 characterized by large amplitude variations of the four measured proxies occur
223 between 7 and 8 cm, between 10.5 and 12.4 cm, between 18 and 20 cm and
224 between 34 and 36 cm (blue lines Fig. 3). Between 7 and 8 cm and between 34
225 and 36 cm, calcite aspect is dark compact with almost no visible layering. During
226 these two intervals layer thickness decreases to 0.2 mm/layer and the $\delta^{18}\text{O}$ and
227 $\delta^{13}\text{C}$ values increase to values around -6.0 ± 0.16 ‰ and -8.0 ± 0.12 ‰
228 respectively. Between 10.5 and 12.4 cm, calcite is heavily altered and more matte
229 and whiter compared to the generally more translucent calcite aspect of the
230 Proserpine. The heat of the fires made on the surface of the stalagmite during the
231
232

233 perturbation period may have altered the calcite in this part. In this interval,
234 layer thickness decreases to 0.2 mm/layer and the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values increase
235 to values around $-6.0 \pm 0.16 \text{ ‰}$ and $-6.5 \pm 0.12 \text{ ‰}$ respectively. From 18 to 20
236 cm, layering is heavily undulating with vertically orientated layers in some parts,
237 which may reflect small basin or rimstone structures. In this interval, layer
238 thickness decreases to 0.4 mm/layer and the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values increase
239 sharply to $-6.2 \pm 0.16 \text{ ‰}$ and $-7.0 \pm 0.12 \text{ ‰}$ respectively. With the exception of
240 the four intervals characterized by simultaneous large amplitude variations of
241 the four measured proxies, the time-series can be subdivided in two parts. For
242 the part above the perturbation (part I), calcite aspect is generally darker and
243 more compact. The $\delta^{18}\text{O}$ values average $-6.6 \pm 0.16 \text{ ‰}$ and $\delta^{13}\text{C}$ values average
244 $-10 \pm 0.12 \text{ ‰}$. Both display a good correlation as indicated by a Spearman's
245 correlation coefficient of $\rho = 0.811$ ($p = 8.86 \times 10^{-44}$). Layer thickness in part I
246 averages 0.3 mm/layer and displays similar variations as the isotopes with
247 thicker layers corresponding with more negative isotopic values. The parts
248 below the perturbation (parts II to VII) display more negative $\delta^{18}\text{O}$ values at
249 $-7.0 \pm 0.12 \text{ ‰}$ while the $\delta^{13}\text{C}$ values vary around the same mean of $-10 \pm 0.12 \text{ ‰}$. A
250 lower Spearman's correlation coefficient between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals is
251 calculated for these parts (parts II to VII) ($\rho = 0.37$, $p = 9.54 \times 10^{-24}$). Below the
252 perturbation, layer thickness varies between 0.5 and 1 mm/layer and displays
253 similar variations as the $\delta^{18}\text{O}$ values. In lower part II and the upper part III (14 -
254 18.5 cm) and for the most of part V, part VI and VII (38 - 56 cm), the $\delta^{18}\text{O}$ signal is
255 generally more negative ($-7.5 \pm 0.16 \text{ ‰}$) and the layer thickness increases to 0.8
256 mm/layer (Fig. 3). In the lower part III and part IV (18.5 and 38 cm), the $\delta^{18}\text{O}$
257 values increase to $-6.6 \pm 0.16 \text{ ‰}$ and the layer thickness decreases to 0.5
258 mm/layer, while no general particular change is observed for the $\delta^{13}\text{C}$ values.
259 Sampling for the stable isotopes was done layer per layer in the parts II to VII
260 and reflects seasonal variations in the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals ([for a high-resolution
261 picture of the seasonally resolved isotope records, the authors refer to Fig. 4 in
262 Van Rampelbergh et al., 2014](#)). The $\delta^{13}\text{C}$ seasonality evolves differently from the
263 $\delta^{18}\text{O}$ seasonality. A larger $\delta^{18}\text{O}$ -seasonality of 0.5 ‰ occurs in the lower part II
264 and upper part III (14 - 18.5 cm) and for the most of part V, part VI and VII (38 -
265 56 cm), while in lower part III to IV (18.5 - 32 cm), the $\delta^{18}\text{O}$ seasonality lowers to
266 0.25 ‰. For $\delta^{13}\text{C}$, the overall seasonality averages at 0.7 ‰. An increase in $\delta^{13}\text{C}$
267 seasonality to 1.5 ‰ occurs at 32 cm and is followed by a gradual decrease until
268 27 cm when the seasonality returns to 0.7 ‰.
269
270
271
272
273
274



275
 276 Figure 2. The upper laminated 56 cm of the Proserpine core with the description
 277 of the calcite aspect. The blue bars indicate intervals during which calcite
 278 deposition is disturbed or calcite aspect is very dark compact or white matte.
 279



280
 281 Figure 3. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals (‰ VPDB) and layer thickness of the
 282 Proserpine core plotted against distance from top. Blue bars indicate intervals
 283 during which the calcite aspect, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signals and layer thickness all
 284 display simultaneous large amplitude variations.
 285

286 Eight U/Th-ages that were previously published by some of us (Verheyden et al.,
 287 (2006) are used and numbered 1, 2, 7, 8, 15, 17, 18 and 19, and marked in light
 288 grey in Table 1. Twelve new U/Th ages measured in this study are listed in black
 289 in Table 1 and correspond well with the previously measured ages. Layer
 290 counting ages were carried out per part (i.e. part I to part VII) and are listed in
 291 Table 2 (column 5) together with their 2 σ uncertainty range. To compare the
 292 two independent age methods (layer counting method and U/Th-age method),
 293 the U/Th-age points have to be interpolated to obtain an age for the top and
 294 bottom of each part. The interpolation of the measured U/Th-ages was carried
 295 out using StalAge and top and bottom ages of each part are listed in Table 2
 296 (column 3). The difference between the top and the bottom age of each part
 297 provides the number of years of that part (Table 2, column 4). The **number**
 298 years per part derived from the U/Th-ages display larger 2 σ uncertainties for the
 299 parts I, II and III (~ 70) compared to the parts IV to VII where uncertainties are
 300 smaller (~ 30). The **number** of years per part derived from the layer counting
 301 display 2 σ uncertainties of ~ 7, being smaller than the uncertainties on the U/Th-
 302 ages. The obtained **number** of layers per part correspond for the two methods in
 303 the parts I, II, II, V and VII. Note that, the U/Th-age method suggests much
 304 smaller **number** of years (Table 2, columns 4 and 5) in the parts IV and VI.
 305

²³⁰Th dating results. The error is 2 σ error.

Sample Number	STM PART	Distance mm	²³⁸ U (ppb)	²³² Th (ppt)	²³⁰ Th / ²³² Th (atomic x10 ⁻⁶)	$\delta^{234}\text{U}^*$ (measured)	²³⁰ Th / ²³⁸ U (activity)	²³⁰ Th Age (vr) (uncorrected)	²³⁰ Th Age (vr) (corrected)**	²³⁰ Th Age (vr AD) (corrected)
1	I	15	154 \pm 0.1		5.2 \pm 0.2	1390.7 \pm 1.8	0.0036 \pm 0.0002	164 \pm 8	42 \pm 70	1971 \pm 70
2	I	60	119 \pm 0.2		9.8 \pm 0.4	1396 \pm 4	0.0043 \pm 0.0002	194 \pm 7	119 \pm 44	1894 \pm 44
3	I	86	66.8 \pm 0.1	1444 \pm 29	9 \pm 1	1382.8 \pm 3.3	0.0118 \pm 0.0003	540 \pm 13	276 \pm 187	1737 \pm 187
4	II	112	52.4 \pm 0.1	260 \pm 5	20 \pm 1	1400.4 \pm 4.2	0.0060 \pm 0.0003	275 \pm 13	215 \pm 45	1798 \pm 45
5	II	130	42.9 \pm 0.1	124 \pm 3	36 \pm 2	1393.0 \pm 5.6	0.0063 \pm 0.0004	288 \pm 17	253 \pm 30	1760 \pm 30
6	III	195	41.4 \pm 0.1	316 \pm 6	20 \pm 1	1275.9 \pm 3.7	0.0091 \pm 0.0004	435 \pm 17	337 \pm 71	1676 \pm 71
7	IV	245	42.6 \pm 0.1		44 \pm 2	1329.4 \pm 2.3	0.0087 \pm 0.0004	408 \pm 17	379 \pm 30	1634 \pm 30
8	IV	275	57.2 \pm 0.1		41 \pm 2	1347.7 \pm 4.1	0.0092 \pm 0.0004	430 \pm 18	396 \pm 30	1617 \pm 30
9	IV	332	65.3 \pm 0.1	171 \pm 4	55 \pm 2	1309.7 \pm 4.2	0.0087 \pm 0.0003	411 \pm 12	378 \pm 26	1635 \pm 26
10	V	342	55.1 \pm 0.1	83 \pm 2	94 \pm 3	1395.5 \pm 3.3	0.0086 \pm 0.0002	393 \pm 11	374 \pm 17	1639 \pm 17
11	V	360	38.8 \pm 0.1	173 \pm 4	38 \pm 1	1401.4 \pm 4.4	0.0103 \pm 0.0003	469 \pm 15	415 \pm 41	1598 \pm 41
12	V	399.2	44.6 \pm 0.1	167 \pm 3	48 \pm 2	1398.5 \pm 3.2	0.0108 \pm 0.0003	494 \pm 15	449 \pm 35	1564 \pm 35
13	VI	433.5	40.6 \pm 0.1	72 \pm 2	98 \pm 4	1394.2 \pm 4.3	0.0106 \pm 0.0004	482 \pm 18	460 \pm 23	1553 \pm 23
14	VI	493.5	43.7 \pm 0.1	86 \pm 2	91 \pm 4	1406.2 \pm 3.7	0.0109 \pm 0.0004	495 \pm 17	471 \pm 24	1542 \pm 24
15	VI	510	46.7 \pm 0.1		185 \pm 19	1402.9 \pm 4.2	0.0096 \pm 0.0005	439 \pm 23	440 \pm 24	1573 \pm 24
16	VII	518	38.6 \pm 0.1	79 \pm 2	88 \pm 4	1402.9 \pm 4.5	0.0109 \pm 0.0005	497 \pm 23	472 \pm 29	1541 \pm 29
17	VII	530	52.3 \pm 0.1		184 \pm 11	1409.8 \pm 3.0	0.0101 \pm 0.0004	459 \pm 18	460 \pm 19	1553 \pm 19
18	VII	540	52.6 \pm 0.1		188 \pm 11	1392.8 \pm 3.3	0.0105 \pm 0.0004	481 \pm 18	482 \pm 19	1531 \pm 19
19	VII	560	47.5 \pm 0.1		219 \pm 19	1394.9 \pm 4.2	0.0113 \pm 0.0005	515 \pm 22	517 \pm 23	1496 \pm 23
20	VII	560	45.9 \pm 0.1	42 \pm 1	208 \pm 10	1384.7 \pm 4.1	0.0115 \pm 0.0004	525 \pm 20	514 \pm 21	1499 \pm 21

U decay constants: $\lambda_{238} = 1.55125 \times 10^{-10}$ (Jaffey et al., 1971) and $\lambda_{234} = 2.82206 \times 10^{-6}$ (Cheng et al., 2013). Th decay constant: $\lambda_{230} = 9.1705 \times 10^{-6}$ (Cheng et al., 2013).

* $\delta^{234}\text{U} = ((^{234}\text{U}/^{238}\text{U})_{\text{activity}} - 1) \times 10000$. ** $\delta^{234}\text{U}_{\text{initial}}$ was calculated based on ²³⁰Th age (T), i.e., $\delta^{234}\text{U}_{\text{initial}} = \delta^{234}\text{U}_{\text{measured}} \times e^{230\lambda T}$. Corrected ²³⁰Th ages assume the initial ²³⁰Th/²³²Th atomic ratio of 4.4 \pm 2.2 $\times 10^{-6}$. Those are the values for a material at secular equilibrium, with the bulk earth ²³²Th/²³⁸U value of 3.8. The errors are arbitrarily assumed to be 50%.

** Ages are reported before 2013

306 Table 1. U/Th measurements (University of Minnesota) of the Proserpine
 307 stalagmite. All ages are converted to before 2013. Ages number 1, 2, 7, 8, 15, 17,
 308 18 and 19, marked in light grey are the U/Th-ages from Verheyden et al., 2006.
 309

310 The growth rates per part derived from the U/Th-ages are listed in Table 2,
 311 column 6. The growth rates per part derived from the layer counting ages are
 312 listed in Table 2, column 7. The growth rates per part based on layer counting
 313 increase in two steps: they are low at 0.6 mm/y in part I, higher around 1 mm/y
 314 in part II, III and IV, and very high at 2 mm/year in the parts V, VI, and VII. The
 315 growth rates per part derived from the U/Th-ages display much larger variations
 316 between the different parts, with exceptionally high growth rates of 5.6 mm/y
 317 for the part IV and of 6.5 mm/y for part VI.
 318
 319

Part	Depth (cm)	U/Th-ages interpolated years AD $\pm 2\sigma$	Amount of years U/Th-ages per part years $\pm 2\sigma$	Amount of years layer counting per part years $\pm 2\sigma$	Growth Rate U/Th-ages (mm/y)	Growth Rate Layer Counting (mm/y)
I	0	2001 ± 0				
	9	1822 ± 60	179 ± 60	144 ± 6	0,5 \pm 0,2	0,6 \pm 0,03
II	10	1810 ± 48				
	16,2	1723 ± 73	87 ± 87	66 ± 6	0,7 \pm 0,7	0,9 \pm 0,08
III	16,2	1717 ± 70				
	22,4	1655 ± 33	62 ± 77	41 ± 5	1,0 \pm 1,2	1,5 \pm 0,20
IV	22,4	1650 ± 29				
	33,6	1631 ± 16	19 ± 33	105 ± 7	5,9 \pm 1	1,1 \pm 0,01
V	33,6	1629 ± 15				
	41,3	1567 ± 21	62 ± 25	48 ± 4	1,3 \pm 0,5	1,6 \pm 0,13
VI	41,3	1567 ± 22				
	50	1553 ± 16	13 ± 27	42 ± 10	6,5 \pm 13	2,1 \pm 0,5
VII	50	1553 ± 16				
	56	1501 ± 17	53 ± 23	27 ± 8	1,1 \pm 0,5	2,2 \pm 0,6

Table 2. Comparison between the layer counting ages and U/Th-ages per part together with their growth rates. The interpolated U/Th-ages for the top and the bottom of each part were obtained using StalAge. All values are reported with their 2σ uncertainty range.

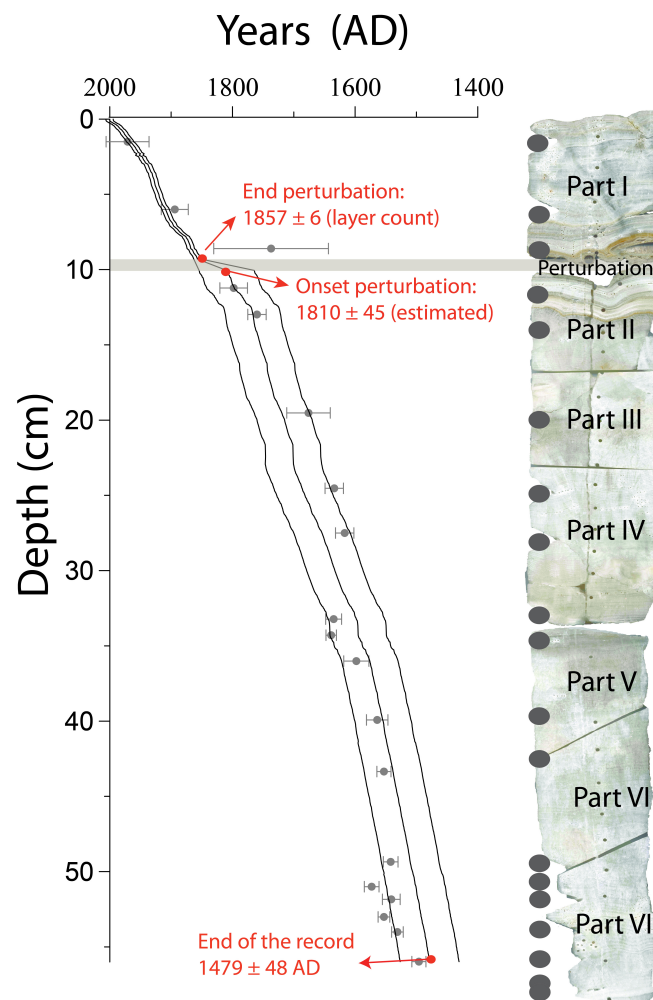
5. Discussion

5.1 Speleothem Age model

Two independent geochronological methods are used to establish the age model of the Proserpine: StalAge based on 20 U/Th-ages and layer counting. Due to the interruption in calcite deposition between 9 and 10 cm, the layer counting ages cannot be used to count the years back from present until 56 cm. Apart from this interruption in deposition, the continuous layering was visible throughout the full length of the core at least in part across the 10 cm width of the slab. The absence of visible indications of interruptions of deposition, the high growth rate of the order of 1 mm per year, and the present day high drip rate, encouraged us to use layer counting as a reliable and precise geochronological approach. Moreover we could rely on previous work by some of us (Van Rampelbergh et al., 2014) that demonstrated that all layer duplets, consisting of a lighter and a darker one, correspond to one year. To compare the U/Th-ages and the layer counting ages, the number of years must be determined for each part (Table 2, columns 4 and 5). Results show that the layer counting method displays smaller uncertainties. Both independent geochronological methods deliver similar ages with the exception of parts IV and VI, where the U/Th-ages suggest a lower number of years. The U/Th-ages indicate that Part IV was deposited in 19 ± 33 years while the layer counting indicates a total of 105 ± 7 years (Table 2). The U/Th-ages suggest that Part VI was deposited in 13 ± 27 years while the layer counting indicates a total of 42 ± 10 years (Table 2). The number of years obtained by layer counting in the two parts IV and VI is considered more probable compared to the number of years obtained by U/Th ages. Based on in-situ monitoring of the Proserpine drip site demonstrating the seasonal character of the layering and the good agreement of the layer counting and the U/Th ages in most of the other parts, the layer counting model is seen as the most accurate to establish the chronology. Furthermore, the U/Th ages give improbable high growth rates (~ 6 mm/y) for the parts IV and VI (Table 2).

Using the layer counting ages, the Proserpine age model is subdivided in two parts: the part above the perturbation and the part below the perturbation. The age of part I above the perturbation can be obtained by simply counting the

361 layers back from 2011. This leads to an age of 1857 ± 6 AD for the end of the
 362 perturbation (Fig. 4). Below the perturbation (at 10 cm), the age of the onset of
 363 the perturbation has to be estimated in order to restart the layer counting
 364 downwards. This is carried out by counting the layers back upward from the
 365 U/Th-age located closest below the perturbation ($=1798 \pm 45$ AD). By doing this,
 366 a total of 12 ± 2 layer-couplets are obtained, indicating that the age of the onset
 367 of the perturbation is estimated at 1810 ± 45 AD (Fig. 4). The good estimation of
 368 this age is confirmed by the fact that StalAge suggests an age of 1810 ± 48 AD for
 369 the onset of the perturbation. Furthermore, a ^{14}C -date on a straw piece
 370 embedded in the perturbed calcite indicates an age interval of 1760 to 1810
 371 (probability of 95.4 %) (Verheyden et al., 2006) also suggesting a similar time
 372 window for the perturbation. The age of 1810 ± 45 AD is consequently
 373 considered a good estimation of the onset of the perturbation. This age is used to
 374 restart layer counting downwards. Since the uncertainties on the layer counting
 375 ages are determined per part, the uncertainty on the age model increases per
 376 additional older part according to the propagation of uncertainties on a sum
 377 (Table 3). The age obtained for the bottom of the laminated part of the
 378 Proserpine stalagmite at 56 cm is 1479 ± 48 AD (Fig. 4).
 379



380
 381 Figure 4. Age-depth model of the Proserpine based on layer counting ages
 382 reported with their 2σ uncertainty. The onset of the perturbation is estimated by
 383 counting the layers back up from the U/Th-age located closest below the

384 perturbation. U/Th-ages are plotted in light grey in the age-depth graph with
 385 their 2σ uncertainty. Location of U/Th samples on the Proserpine core is
 386 indicated by the black dots. All ages are reported in years AD.
 387

Part	Uncertainty on counted layers per part $\pm 2\sigma$	Uncertainty on obtained ages (AD) per part $\pm 2\sigma$
II	± 6	Starting point 1810 ± 45 AD ± 45
III	± 5	± 45
IV	± 7	± 46
V	± 4	± 46
VI	± 10	± 47
VII	± 8	± 48

388
 389 Table 3. Uncertainties on the counted layers per part below the perturbation (II
 390 to VII) together with the uncertainties on the obtained ages (AD) per part using
 391 the age of 1810 ± 45 AD as starting point for the age model counting.
 392

393 5.2 Factors driving decadal and multi-decadal changes in the measured 394 proxies 395

396 Variations in $\delta^{18}\text{O}$ values of speleothems deposited in equilibrium with their drip
 397 water relate mainly to changes in air temperature, rainfall amount and/or source
 398 of the rainfall (Fairchild et al., 2006). Rainfall sources often imply $\delta^{18}\text{O}$ shifts in
 399 the order of several ‰ (Fleitmann et al., 2007) while the $\delta^{13}\text{C}$ values and layer
 400 thickness values remain unchanged. The large-scale $\delta^{18}\text{O}$ variations in the
 401 Proserpine are in the order of 1 to 2 ‰ and always occur together with large-
 402 scale $\delta^{13}\text{C}$ variations of the same order and a decrease in layer thickness
 403 indicating that the source effect is most probably not responsible for these $\delta^{18}\text{O}$
 404 variations. In temperate regions speleothem $\delta^{18}\text{O}$ values often display a difficult
 405 link with surface air temperature due to the inverse effect of temperature on the
 406 rainwater $\delta^{18}\text{O}$ compared to the calcite $\delta^{18}\text{O}$. The relation between surface air
 407 temperature and rainwater $\delta^{18}\text{O}$ varies between ~ 0.1 and 0.3 ‰/1 °C for
 408 Central Europe (Schmidt et al., 2007). The temperature dependent fractionation
 409 during calcite formation within the cave acts in the opposite direction, and is
 410 around -0.2 ‰/1 °C for the Proserpine drip site as suggested by monitoring
 411 results (Van Rampelbergh et al., 2014). The net effect of air temperature changes
 412 on the Proserpine $\delta^{18}\text{O}$ signal may thus vary between ~ -0.1 and 0.1 ‰/1 °C
 413 considering that the temperature dependence of the rainwater of ~ 0.1 and 0.3
 414 ‰/1 °C is also valid for Belgium. Consequently, the temperature effect most
 415 probably only has a minor influence on the decadal and multi-decadal variations
 416 in the Proserpine $\delta^{18}\text{O}$ signal. In the studied region, **more positive** $\delta^{18}\text{O}$ values
 417 have been observed to correspond to drier periods and thus reflecting the
 418 amount effect (Verheyden, 2001). Variations in the Proserpine $\delta^{18}\text{O}$ may thus
 419 possibly relate to changes in wetter or drier conditions.
 420

421 If recharge is seasonally biased, the decadal and multi-decadal $\delta^{18}\text{O}$ variations
422 may be caused by variations in air temperature and/or by rainfall amount during
423 a certain season. Hydrological studies of the Han-sur-Lesse epikarst show that
424 recharge mostly occurs between spring and fall with largest amounts of recharge
425 in winter (Bonniver, 2011). Rainfall $\delta^{18}\text{O}$ data show that winter rainfall has a
426 **more negative $\delta^{18}\text{O}$ value** compared to the rainfall from other seasons (Van
427 Rampelbergh et al., 2014). During a period of lower winter recharge, less
428 isotopically **more negative** (winter) water is added to the epikarst reservoir
429 compared to the **more positive** spring and fall water and the total $\delta^{18}\text{O}$ of the
430 epikarst water increases, causing **less negative** $\delta^{18}\text{O}$ values in the speleothem.
431 Periods of increased $\delta^{18}\text{O}$ values in the Proserpine record may thus be reflecting
432 drier winter periods and vice versa. The relation between lower drip water $\delta^{18}\text{O}$
433 and higher winter recharge amounts can be illustrated by drip water monitoring
434 data over several years. Although no such data **are** available, winter recharge is
435 considered the main factor determining the $\delta^{18}\text{O}$ values of the Proserpine. More
436 positive $\delta^{18}\text{O}$ values are interpreted to reflect drier winter periods and vice
437 versa. Furthermore, a good Spearman correlation can be established between
438 lower winter precipitation intensities (DJF) and lower winter temperatures
439 (DJF) measured by the RMI since 1833 ($\rho = 0.47$ and $p = 3.99 \times 10^{-11}$) suggesting
440 that drier winters correspond to colder winters. More negative $\delta^{18}\text{O}$ values in the
441 Proserpine may thus possibly reflect drier winter conditions that are most
442 probably also colder. A similar interpretation is used for the decadal and
443 centennial $\delta^{18}\text{O}$ variations measured **in** a German speleothem with similar yearly
444 temperature and yearly precipitation amounts as the Proserpine growth site
445 (Wackerbarth et al., 2010; Fohlmeister et al., 2012).

446
447 Since no major vegetation changes (mainly C3-vegetation) occurred above the
448 cave for **the** studied period and site, changes in $\delta^{13}\text{C}$ values might relate to
449 changes in soil activity (Genty et al., 2003; Fohlmeister et al., 2012) and/or Prior
450 Calcite Precipitation (PCP) (Fairchild et al., 2000). Plant- CO_2 has a **more negative**
451 **$\delta^{13}\text{C}$ value than** atmospheric CO_2 ($\delta^{13}\text{C}$ of C3-vegetation is between -20 and -
452 25‰, while in atmospheric CO_2 it evolved **roughly** from -7 ‰ to -8 ‰ during
453 the studied period). A reduced plant- CO_2 input in the soil due to lower soil
454 activity will increase the $\delta^{13}\text{C}$ of the soil- CO_2 reservoir and consequently **the $\delta^{13}\text{C}$**
455 **of** the dissolved inorganic carbon (DIC) in the epikarst water. During PCP, calcite
456 is deposited from the percolating epikarst water before entering the cave as drip
457 water. This process mostly occurs during drier periods when aerated zones
458 become more important in the epikarst. PCP causes a simultaneous increase in
459 the $\delta^{13}\text{C}$ and in the Mg/Ca and Sr/Ca composition of the drip water and
460 speleothem calcite (Fairchild et al., 2000). Although no Mg/Ca and Sr/Ca ratios
461 are measured in the Proserpine, which makes it difficult to evaluate the process
462 of PCP, monitoring results have clearly demonstrated that PCP is an important
463 process in the Han-sur-Lesse epikarst (Van Rampelbergh et al., 2014). Both
464 effects, being soil activity and PCP act in the same direction and both cause the
465 $\delta^{13}\text{C}$ values to increase during drier periods. Since drier periods in the cave are
466 caused by lower winter recharge periods, increased $\delta^{13}\text{C}$ values are interpreted
467 to reflect drier and most probably also colder winter periods. **This interpretation**
468 **is also supported by the observations made by some of us** (Verheyden et al.,

469 2014), and referred to in the Introduction, in a speleothem in the Père Noël cave,
470 which is part of the same Han-sur-Lesse cave system, in which the similarly
471 varying isotopic ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) and geochemical (Mg/Ca and Sr/Ca) proxies
472 could be interpreted in terms of alternations of wetter and drier phases, causing
473 changes between weaker or absent PCP and more intense PCP respectively.
474

475 Disequilibrium processes due to a stronger pCO_2 gradient between the cave air
476 and drip water and/or due to longer drip intervals may cause simultaneously
477 increased $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values (Mühlinghaus et al., 2009; Scholz et al., 2009;
478 Deininger et al., 2012). Under the present-day conditions, pCO_2 levels of the cave
479 air in the Salle-du-Dôme are low year-round and equal the outside air values.
480 pCO_2 levels may change over time due to changes in ventilation patterns, which
481 may change over time due to new cave openings. No such new openings that may
482 have affected the Salle-du-Dôme ventilation occurred in the last 500 years. The
483 effect of changing pCO_2 gradient on the drip water $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values over the
484 studied period is thus unlikely. Longer drip intervals due to decreased drip flow
485 may be possible. However, under the present-day conditions, a continuous high
486 drip water flow feeds the stalagmite, which inhibits disequilibrium effects
487 related to longer drip interval (Mühlinghaus et al., 2009). The drip discharge
488 consequently needs to have sufficiently decreased, beneath a certain threshold
489 value, to allow disequilibrium processes to occur. Since recharge occurs in
490 winter (Bonniver, 2011), a decreased drip discharge is expected to relate with
491 significantly drier winters, that are most probably also colder. Furthermore,
492 during periods of lower drip discharge, PCP will occur and further increase the
493 $\delta^{13}\text{C}$ signal. Decreased drip discharge due to significantly drier (and colder)
494 winters will consequently cause increased correlating $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values with
495 a larger increase in $\delta^{13}\text{C}$ values compared to the $\delta^{18}\text{O}$ values, the latter being not
496 affected by PCP.
497

498 Layer thickness and calcite aspect in the Proserpine are expected to relate to
499 growth rate, with thinner layers and darker calcite formed under slower growth.
500 Growth rate is primarily dependent on two factors; the discharge amount, which
501 is expected to lower during drier (and colder) winter periods and the cave
502 seepage water calcium ion concentration (Genty et al., 2001). The cave seepage
503 water calcium ion concentration depends on mainly two factors. The first factor,
504 being the soil pCO_2 is expected to increase during warmer and wetter periods.
505 Higher soil pCO_2 increases the amount of CO_2 dissolved in the soil water. Water
506 containing higher CO_2 amounts more easily dissolves CaCO_3 , which increases its
507 calcium ion concentration. The second factor determining seepage water calcium
508 ion concentration is the intensity of PCP. PCP mostly occurs during dry periods
509 and decreases the Ca^{2+} concentration of the drip water due to precipitation of
510 calcite in the epikarst. Cave monitoring results show that PCP is an important
511 process in the Han-sur-Lesse epikarst that becomes more intense during the
512 drier summer season (Van Rempelbergh et al., 2014). During drier periods, most
513 probably caused by drier (and colder) winter periods, soil activity will decrease
514 and PCP will increase, both causing lower calcium ion concentration of the drip
515 water. A lower calcium ion concentration and a lower drip discharge during
516 drier (and colder) winters will both cause slower calcite deposition and
517 consequently thinner layers and darker calcite.

518

519 To conclude, decadal and centennial changes in the proxies ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$
520 signals, layer thickness and calcite color) reflect changes in drier (and colder)
521 versus wetter (and warmer) winters. Exceptionally dry (and cold) winters shift
522 the drip discharge below a certain threshold value, which causes the proxies to
523 display simultaneous large amplitude shifts. During such exceptionally dry (and
524 cold) winter periods, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values increase, layer thickness decreases
525 and calcite aspect becomes darker and/or disturbed. When the discharge
526 threshold is not reached, calcite is deposited close to equilibrium and the four
527 proxies may vary independently.

528

529 **5.3 Anomalies in the proxy records**

530

531 Proserpine calcite deposited in equilibrium with its drip water has a $\delta^{18}\text{O}$ value
532 of $-6.7 \pm 0.16 \text{ ‰}$ and a $\delta^{13}\text{C}$ value of $-10 \pm 0.12 \text{ ‰}$ (Van Rampelbergh et al.,
533 2014). Four periods where the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values abruptly increase away from
534 the present-day equilibrium occur in the Proserpine from 1565 to 1610, at 1730,
535 from 1770 to 1800 and from 1880 to 1895 and are interpreted as anomalies in
536 the record (blue bars Fig. 5). During these anomalies layer thickness decreases
537 below 0.2 mm/layer and calcite aspect is disturbed or very dark and compact. As
538 indicated by the detailed analysis of the climatic factors affecting the different
539 used proxies, as soon as a certain threshold value is reached, the four proxies
540 display simultaneous large-amplitude changes and reflect exceptionally dry (and
541 cold) winter periods. No calcite was deposited between 1810 and 1860, which
542 strongly suggests that too little water was dripping on the Proserpine during that
543 period. Therefore, this period is also interpreted as an anomaly reflecting
544 exceptionally dry (and cold) winters. A total of five anomalies are suggested by
545 the Proserpine proxies and last between 1565 and 1610, at 1730, between 1770
546 and 1800, between 1810 and 1860 and between 1880 and 1895 (blue bars Fig.
547 5). The five anomalies suggesting exceptionally dry (and cold) winter conditions
548 correspond with known cold and/or dry periods in historical and instrumental
549 archives and in winter temperature reconstructions from Europe and Central
550 Europe (Fig. 5):

551

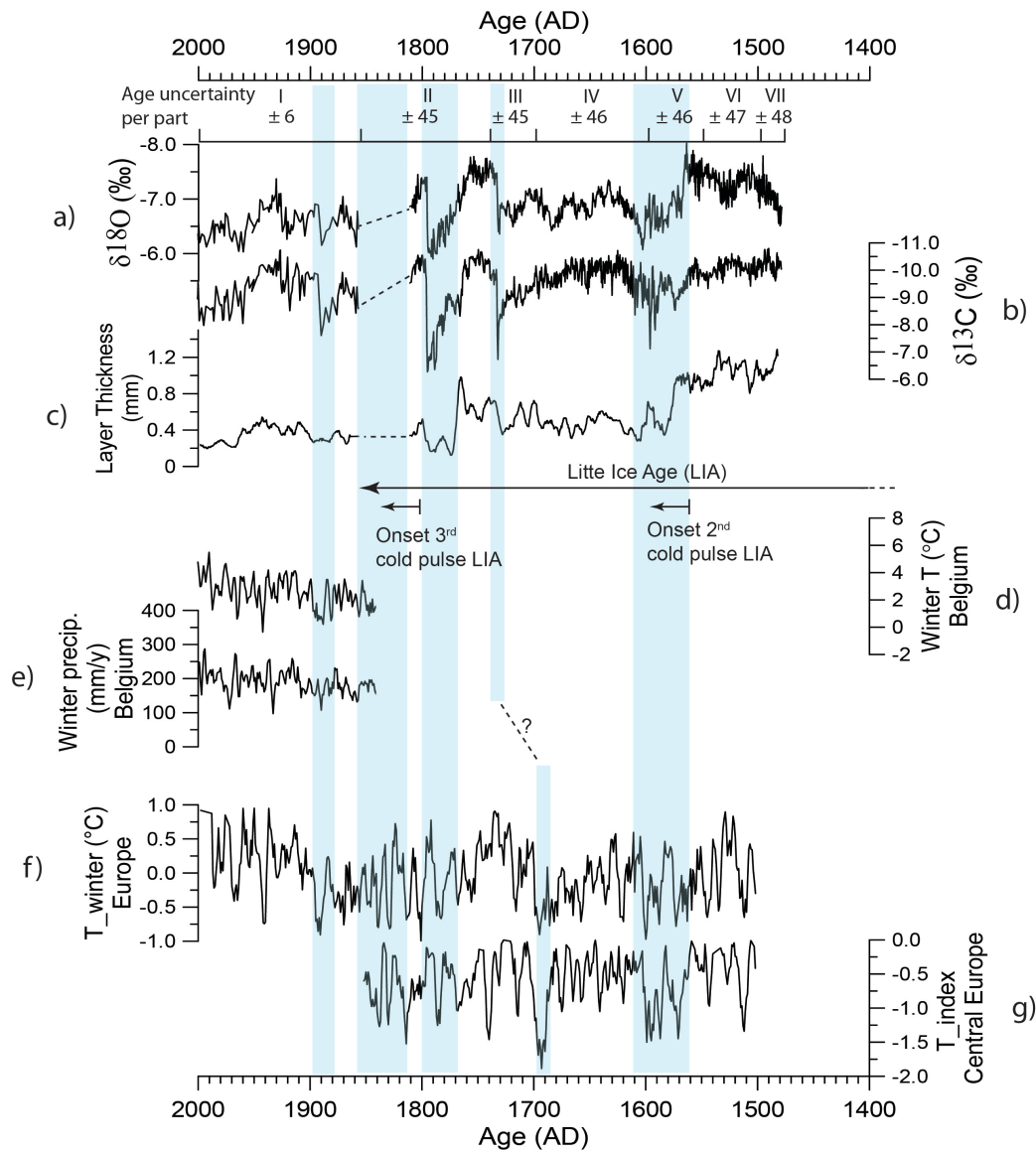
- 552 • Between 1565 and 1610 winter temperatures in Europe (Luterbacher et
553 al., 2004) and Central Europe (Dobrovolny et al., 2010) were low (Fig. 5, f
554 and g). Historical data of France, Belgium and the Netherlands indicate icy
555 cold winters, harsh famines, low numbers of child births and weddings,
556 and the outbreak of the plague with its worst years from 1562 to 1570
557 (Le Roy Ladurie, 2004). The shift to cold and dry conditions at 1565 AD is
558 interpreted as the onset of the second pulse of the Little Ice Age (LIA,
559 ± 1300 -1850) (Le Roy Ladurie, 2004) and is nicely recorded in the
560 Proserpine proxies as a shift to drier (and colder) winters. Between 1590
561 and 1600, the Proserpine proxies suggest a shorter wetter (and warmer)
562 interval as indicated by the more negative $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values and
563 thicker layers (Fig. 5 a, b and c). A similar decade of warmer conditions
564 between 1590 and 1600 is also reported in winter temperature
565 reconstructions from Europe (Luterbacher et al., 2004), Central Europe

566 (Dobrovolny et al., 2010) and from historical archives (Le Roy Ladurie,
567 2004).

- 568 • At 1730, the abrupt shift in the measured proxies suggests a short but
569 exceptionally dry (and cold) winter period. Considering the age
570 uncertainty of ± 45 years for this period (Fig. 5), the dry (and cold)
571 conditions suggested by the Proserpine at 1730 ± 45 AD, most probably
572 relate to the exceptionally cold and dry decade between 1690 and 1700
573 AD recorded in historical archives (Le Roy Ladurie, 2004) and by
574 extremely low winter temperatures in Europe (Luterbacher et al., 2004)
575 and Central Europe (Dobrovolny et al., 2010) (Fig. 5, f and g).
- 576 • Between 1770 and 1800, the Proserpine proxies suggest a dry (and cold)
577 winter period that corresponds to a known period of colder winters in
578 Europe (Fig. 5, f and g) (Le Roy Ladurie, 2004; Luterbacher et al., 2004;
579 Dobrovolny et al., 2010).
- 580 • The exceptionally dry (and cold) winter conditions between 1810 and
581 1860, as suggested by the Proserpine, correspond nicely with decreased
582 winter temperatures in Europe (Luterbacher et al., 2004) and Central
583 Europe (Dobrovolny et al., 2010) (Fig. 5, f and g). Historical climate data
584 from France, Belgium and the Netherlands indicate that this interval
585 corresponds with the third and last cold pulse of the LIA and is
586 characterized by exceptionally cold winters and warm summers (Le Roy
587 Ladurie, 2004).
- 588 • The most recent dry (and cold) period recorded in the Proserpine (1880
589 and 1895) corresponds with colder winter temperatures and lower
590 winter precipitation amounts as measured by the RMI in Belgium since
591 1833 (Fig. 5, d and e). The temperature drop is clearly visible in the
592 winter temperature reconstruction from Europe (Luterbacher et al.,
593 2004) (Fig. 5, f). A decrease in precipitation has also been recorded in the
594 England and Wales precipitation record, where this period is known as
595 very dry with peak dry years at 1884, 1887 and 1893 (Nicholas and
596 Glasspoole, 1931).

597
598
599 The exact forcing behind these five dry (and cold) winter periods is still a matter
600 of discussion. The most trivial forcing of the western European climate is the
601 variation in winter North Atlantic Oscillation (NAO) (Trouet et al., 2009). During
602 a negative winter NAO phase, westerlies winds are forced over southern Europe,
603 which may cause drier and colder winter conditions over Belgium. However, the
604 five dry (and cold) winter periods observed in the Proserpine do not always
605 correspond with negative winter NAO phases (Trouet et al., 2009). Other than
606 negative NAO phases, lower solar irradiance combined with the input of volcanic
607 ejecta in the atmosphere may also be responsible for decreased temperatures in
608 Europe. Such is probably the case for the cold and dry period between 1810 and
609 1860 (third pulse of the LIA). In this period, solar insolation decreased during
610 the Dalton Minimum (1790-1810, Mann, 2002) and the Tamborra volcano
611 (Indonesia) erupted in 1815. Combination of negative NAO conditions
612 (Luterbacher et al., 2001), the eruption of the Krakatoa volcano (Indonesia) in
613 1883 and lower sunspot activity (Lassen and Friischristensen, 1995) are most

614 probably responsible for the exceptionally dry (and cold) winter period between
 615 1880 and 1895.
 616
 617



618
 619
 620 **Figure 5.** The (a) $\delta^{18}\text{O}$ and (b) $\delta^{13}\text{C}$ values (‰ VPDB) and (c) layer thickness
 621 plotted against (d) the instrumental winter temperature (DJF) and (e) winter
 622 precipitation (DJF) record of the Belgian Royal Meteorological Institute (RMI)
 623 measured in Brussels since 1833 (f) the winter temperature reconstruction
 624 based on multiple proxies in Europe (Luterbacher et al., 2004) and (g) the winter
 625 temperature reconstruction derived from documentary and instrumental
 626 evidence in Central Europe (Dobrovolny et al., 2010). Five exceptionally dry (and
 627 cold) winter periods suggested by the Proserpine are indicated by blue bars and
 628 correspond with clear cold periods in instrumental records and winter
 629 temperature reconstructions in Europe and Central Europe. Two periods of
 630 relatively wetter (and warmer) winters occur from 1479 and 1565 and from
 631 1730 to 1770 and correspond with known warmer intervals. Between 1610 and

632 1730 the Proserpine suggests relatively drier (and colder) winter periods, which
633 correspond with colder winter conditions in Europe and Central Europe.

634

635

636

637 **5.4 More gentle alternations of warmer and wetter with colder and drier** 638 **periods**

639

640 In contrast to the five periods where large-amplitude anomalies of the four
641 proxies suggest exceptionally dry (and cold) winter conditions, the remaining
642 parts of the Proserpine stalagmite display more limited variations. Between
643 2001 and 1860, above the perturbation, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values display a bulge
644 with most negative values around 1930. Layer thickness follows the same
645 evolution with the thickest layers around 1930 indicating an evolution to wetter
646 (and warmer) winters up to 1930 followed by an evolution to drier (and colder)
647 winters to 2001. This observation in the Proserpine proxies does not correspond
648 with instrumental winter precipitation and temperature data measured by the
649 RMI since 1833 nor with European winter temperature reconstructions
650 (Luterbacher et al., 2004) (Fig. 5). Calcite is darker in this part due to the
651 incorporation of soot from torches used to illuminate the chamber during cave
652 visits (Verheyden et al., 2006). Soot incorporation in the calcite structure may
653 hamper the calcite deposition and overprint lower-amplitude climate variations.
654 However, large-amplitude variations such as the dry (and cold) winter anomaly
655 between 1880 and 1895 are still visible within this part, indicating that the
656 climate signal is not fully overprinted. The possible effects of soot on $\delta^{18}\text{O}$ and
657 $\delta^{13}\text{C}$ values and layer thickness need further investigation to allow deriving low-
658 amplitude climate variations in the part above the perturbation.

659

660 Below the perturbation, and with exception of the anomaly periods, the
661 measured proxy signals can be subdivided in three periods; between 1479 and
662 1565, between 1610 and 1730 and between 1730 and 1770 (Fig 5 a, b and c).
663 Between 1479 and 1565 and between 1730 and 1770, more negative $\delta^{18}\text{O}$ values
664 and thicker layers indicate relatively wetter (and warmer) winter conditions. In
665 between the two latter periods (1610-1730), the $\delta^{18}\text{O}$ values become less
666 negative and layers become thinner indicating relatively drier (and cooler)
667 winter conditions. During the three above described periods (1479-1565, 1610-
668 1730, 1730-1770), the $\delta^{13}\text{C}$ values display no variations indicating no major
669 changes in soil activity or PCP intensity. Only during the relatively drier (and
670 colder) winter period between 1610 and 1730, the $\delta^{13}\text{C}$ values display a weak
671 gradual increase from 1700 to 1730. The relatively dry (and cool) conditions in
672 the period between 1610 and 1730 may have caused lower soil activity and a
673 gradual increase in prior calcite precipitation, which gradually augment the $\delta^{13}\text{C}$
674 signal.

675

676 The two periods with relatively wetter (and warmer) winters (1479-1565 and
677 1730-1770) interrupted by a period with drier (and cooler) winters (1610-
678 1730) observed in the Proserpine are also recorded in the winter temperatures
679 reconstructions of Europe (Luterbacher et al., 2004) and Central Europe
680 (Dobrovolny et al., 2010)(Fig. 5) and in historical archives (Le Roy Ladurie,

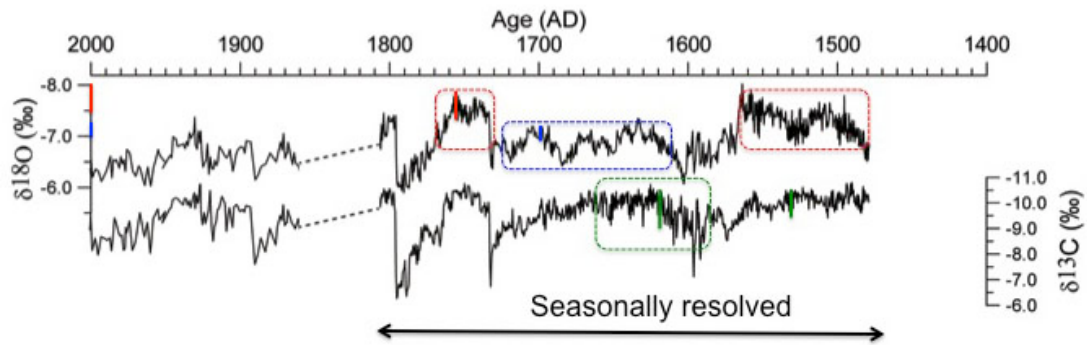
681 2004). The relatively drier (and cooler) winter period between 1610 and 1730
682 corresponds to colder winter conditions in Europe and Central Europe and is
683 referred as the second pulse of the LIA (Le Roy Ladurie, 2004). This relatively
684 cooler interval may relate to the Maunder Minimum, being a period of decreased
685 solar activity between 1640 and 1714. However, lower solar irradiance alone
686 cannot be responsible for the cooler conditions between 1610 and 1730. The
687 exact forcing of this second pulse of the LIA is still a matter of discussions.
688

689 **5.5 Seasonality in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values**

690
691 The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values were measured at a seasonal scale between 1479 and
692 1810 and clearly display seasonal variations (Fig. 6). The interpretation of the
693 $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ variations on a seasonal scale strongly differs from the
694 interpretation of these proxies on decadal and multi-decadal scale. Whereas the
695 decadal and multi-decadal variations in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ vary in phase and reflect
696 changes in drier (and colder) versus wetter (and warmer) winters, the seasonal
697 $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values vary in anti-phase. Seasonal $\delta^{18}\text{O}$ variations are driven by
698 seasonal cave air temperature changes with a temperature dependence of -0.2
699 $\text{‰}/1\text{ }^\circ\text{C}$ (Van Rampelbergh et al., 2014). Higher cave air temperatures in
700 summer lead to lower $\delta^{18}\text{O}$ values of the formed calcite. The seasonal variation in
701 $\delta^{13}\text{C}$ values is driven by the seasonal change in PCP intensity, with stronger PCP,
702 due to drier conditions in summer leading to increased calcite $\delta^{13}\text{C}$ values (Van
703 Rampelbergh et al., 2014).
704

705 The seasonality in $\delta^{18}\text{O}$ measured during the two wetter (and warmer) winter
706 periods (1479-1565 and 1730-1770), equals 0.5 ‰ , which is similar to the
707 present-day conditions (Van Rampelbergh et al., 2014) and corresponds with a 2
708 to $2.5\text{ }^\circ\text{C}$ seasonality in cave air temperature. Between 1610 and 1730, winters
709 are relatively drier (and cooler), and the $\delta^{18}\text{O}$ seasonality lowers to 0.25 ‰
710 corresponding with a 1 to $1.5\text{ }^\circ\text{C}$ cave air temperature seasonality. Lower
711 summer temperatures during this cold LIA period are most probably responsible
712 for the lower cave air seasonality.
713

714 The $\delta^{13}\text{C}$ signal mostly displays a seasonality of 0.7 ‰ being smaller than the 1
715 ‰ seasonality in $\delta^{13}\text{C}$ values observed under the present-day conditions (Van
716 Rampelbergh et al., 2014). At 1600, the $\delta^{13}\text{C}$ seasonality increases to 1.5 ‰ and
717 displays a gradual decreasing trend back to 0.7 ‰ at 1660. The increase in $\delta^{13}\text{C}$
718 seasonality between 1600 and 1660 also corresponds with an interval where
719 layers are thinner ($\sim 0.4\text{ mm/layer}$) but clearly alternating between dark
720 compact and white porous layers. This suggests well-expressed wet winter
721 conditions and dry summer conditions in the cave. The relatively drier (and
722 colder) winter conditions in the period between 1610 and 1730 cause the yearly
723 water recharge (occurring mostly in winter) to be lower compared to the two
724 periods with wetter (and warmer) winters (1479-1565 and 1730-1770). A lower
725 recharge during winter will consequently lead to drier cave conditions in
726 summer, and increase the effect of PCP. Increased PCP in summer due to lower
727 winter recharge is interpreted to be responsible for the increased $\delta^{13}\text{C}$
728 seasonality and the clear layering between 1600 and 1660.



729
 730 Figure 6. A decrease in $\delta^{18}\text{O}$ seasonality in the drier (and cooler) period between
 731 1610 and 1730 (in blue) indicates lower cave air temperature seasonality than
 732 during the wetter (and warmer) periods (1479-1565 and 1730-1770) (in red).
 733 Seasonality in the $\delta^{13}\text{C}$ signal is higher between 1600 and 1660 and indicates
 734 more intense PCP during summer (in green), which is caused by decreased
 735 winter recharge. All values are in ‰ VPDB.

736

737 6. Conclusions

738

739 1. A multiproxy approach using $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values, layer thickness and
 740 calcite aspect, in terms of dark and more compact vs. white and more
 741 porous, of the Proserpine stalagmite from the Han-sur-Less cave, Belgium,
 742 successfully reconstructs the climate over the last 522 years in terms of
 743 drier (and colder) versus wetter (and warmer) winters.

744 2. Thinner layers and darker calcite correspond to periods with decreased
 745 growth rate, driven by lower recharge and stronger PCP effects during
 746 drier (and colder) winters. More positive $\delta^{18}\text{O}$ values are interpreted to
 747 reflect drier (and colder) winters, due to the decreased input of winter
 748 recharge water with more negative isotopic composition. More positive
 749 $\delta^{13}\text{C}$ values reflect lower soil activity and increased PCP during drier (and
 750 colder) winter periods.

751 3. Anomalies in the measured proxies occur when discharge drops under a
 752 certain threshold value. During these anomalies, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values
 753 increase away from isotopic equilibrium, layers become thin and the
 754 calcite becomes very dark or disturbed. Such periods occur between 1565
 755 and 1610, around 1730, between 1770 and 1800, between 1810 and
 756 1860 and between 1880 and 1895 and are interpreted as reflecting
 757 exceptionally dry (and cold) winter conditions. The exceptionally dry
 758 (and cold) periods found in the Proserpine speleothem correspond well
 759 with known dry and cold periods in historical, instrumental and/or
 760 temperature reconstruction records from Europe.

761 4. Less exceptional variations occur between 1479 and 1565 and between
 762 1730 and 1770, with more negative $\delta^{18}\text{O}$ values and thicker layers
 763 reflecting two relatively wetter (and warmer) winters. Less negative $\delta^{18}\text{O}$
 764 values, still reflecting equilibrium conditions, and thinner layers between
 765 1610 and 1730 are interpreted to reflect a period of relatively drier (and
 766 cooler) winters. The two relatively wetter (and warmer) winter periods
 767 correspond with warmer periods in European winter temperature
 768 reconstructions and historical data from Belgium, the Netherland and

769 France. The drier (and cooler) winter period between 1610 and 1730
770 corresponds with relatively colder conditions in winter temperature
771 reconstructions and historical data.
772 5. Seasonally resolved isotopic signals successfully record seasonal changes
773 in cave air temperature and PCP. The $\delta^{18}\text{O}$ signals suggest a 2 to 2.5 °C
774 cave air temperature seasonality between 1479 and 1565 and between
775 1730 and 1770, which is similar to the seasonality in cave air temperature
776 observed today. Between 1610 and 1730, corresponding with a period
777 with drier (and cooler) winters, the seasonality in cave air temperature
778 decreases to 1 to 1.5°C. The $\delta^{13}\text{C}$ seasonal changes suggest that the
779 seasonality in discharge was lower than observed today with a short
780 interval of increased seasonality between 1600 and 1660 reflecting
781 stronger summer PCP-effects due to decreased winter recharge.
782

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788

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