RC1: 'Comment on cp-2024-37', Jasper Wassenburg, 23 Jun 2024

Review Kaushal et al. “Perspective on ice age Terminations from absolute chronologies provided by global speleothem records”.

General comments:

The presented manuscript compiles a global dataset of speleothem ice age Termination records for TII to TV with the purpose of describing chronological sequences of events, discuss differences and similarities between Terminations and the effects of different ice volume corrections. I believe this to be a very valuable contribution that clearly outlines future directions and targets for work on ice age Terminations. In particular, the tuning of other climate archives to speleothem proxies highlights the many purposes of speleothem records. In this regard the authors could, however, indicate some of the potential pitfalls more clearly. For example, correlating climate archives over large distances should be done with caution and only if proven that the different climate parameters respond to the same forcings without delay. The authors suggestion to use isotope enabled climate models for this purpose is indeed a critical one. Overall, the conclusions are well supported by the discussion. I'm looking forward to see this work published with a few revisions.

Dear Prof. Wassenburg,

Thank you for reviewing the article. And thank you for your kind and articulate comments valuing the work presented in this publication. We greatly appreciate your suggestions. We have addressed your comments below. These suggestions will certainly improve the quality of this manuscript.

Specific comments:

My main comment only concerns the structure of the manuscript concerning seawater isotope corrections / ice volume corrections. Right now there is one subchapter (2.2.) devoted to “ice volume corrections”. Within this chapter also P-E changes and its effect on surface seawater d18O is discussed. I believe this subchapter should be named “sea surface d18O corrections” instead, because ice volume directly effects sea surface d18O as well.

Throughout the manuscript there is an ongoing discussion about sea surface d18O corrections. I think it would streamline the paper if everything concerning these corrections could be discussed in chapter 2.2, which ends with a clear conclusion on how every speleothem d18O record is corrected. This also means to move chapter 3.1. to chapter 2.

Thank you for this suggestion. This is something we have considered before as well. This is a long paper with a lot of text, and it took us multiple presentations at workshops (INQUA, EGU) to figure out the clearest way of presenting all the information. We settled on the current format to make clear which datasets had been extracted or modified by us in this manuscript in section 2 versus presenting interpretations in section 3.

Section (2) of the manuscript deals with ‘data processing’. So that subsection 2.1 addresses which data was extracted and used, subsection 2.2 addresses which datasets have been modified to accommodate for ice-volume corrections and subsection 2.3 addresses which datasets have been modified to accommodate for degassing corrections.

Section (3) examines the different climate aspects that have been recorded by speleothems. So that subsection 3.1 addresses records of surface ocean freshening and so on

Subsection 3.1 provides interpretations of the NISA record (which has been used to make corrections as detailed in subsection 2.2) as well as the Villars and Sofular cave records. We will add the Corchia cave record to subsection 3.1 based on Referee 2's comments as well.

However, we realise that subsection 2.2 does not detail which records have been corrected which would make this subsection clearer. We have added a sentence to Line 267 of the revised manuscript as follows (additional sentence highlighted in bold):

Wherever correction for changing δ18Oseawater is implemented, the speleothem data have been binned to 1000, 250 and 125 years respectively to accommodate uncertainties in the speleothem chronology (Supp. Fig. 4). The change in δ18Oseawater as a result of freshening has simply been subtracted from the speleothem δ18O in these bins. Since the uncertainty on sea level curves is much greater than the uncertainty on speleothem age-depth models, only the uncertainty on sea level curves has been considered in these plots. **The ice volume 'corrected' Termination II Abaliget (ABA_1), Sieben Hengste (7H-12), Schneckenloch (SCH-5) and Corchia (CC-5_2018) cave records have been used for further interpretation in the main manuscript and the corrected records are indicated by the Y-axis labels 'd18Ocorr' in the figures. The absence of an equivalent absolute dated record of North Atlantic δ18Oseawater evolution in prior Terminations precludes regional correction of temperature equivalent European records in TIII or older at this time, instead the global ice volume correction has been applied to these records (Supp. Fig. 3).**

Lines 270 – 271: Considering the importance of the NISA d18O record for surface seawater isotope corrections I think it would be helpful to provide more background information why the NISA d18O can be used for this purpose as opposed to only referring to Stoll et al. (2022). Could you please comment on the potential temperature effect on the water to calcite isotope fractionation? A simple sentence that includes the effect of rainfall isotope d18O vs temperature and the cave air temperature water to calcite isotope fractionation would be sufficient. Then the reader who wonders why cave air temperature does not affect CaCO3d18O will readily understand this interpretation as well.

This is a really good suggestion! We have added the following text to Lines 303 of the revised manuscript as follows:

Changes in the δ18Oseawater of the moisture source for caves and drip waters may be the dominant signal in speleothem δ18O in some settings. The δ18O in speleothems from coastal caves in Northwest Spain (NISA) is dominantly controlled by the δ18Oseawater of the eastern North Atlantic, as documented in comparison with independently dated δ18Oseawater records from foraminifera over TI (Stoll et al., 2022). **Rainfall monitoring at this cave location shows that the slight decrease in rainfall d18O with decreasing temperature appears to be of similar magnitude but opposite in sign to the temperature-dependant fractionation between drip water and calcite leaving the δ18Oseawater of the North Atlantic Ocean as the main signal expressed by the speleothems (Stoll et al., 2015; Stoll et al., 2022).** Because of its proximity to the source of meltwater release, the δ18Oseawater of the surface ocean in the North Atlantic experiences a higher amplitude change in δ18Oseawater across a glacial cycle, and may record transient millennial scale events in the δ18Oseawater. Over TII, NISA speleothems provide a record of the timing of deglacial freshening of the eastern North Atlantic with a δ18O amplitude of ~2.5 ‰ (Supp. Fig. 6). Other coastal caves on the Atlantic margin, such as Villars Cave (Supp. Fig. 2), may also be dominated by the change in isotopic composition of the North Atlantic.

Line 325 (and 343 – 345): Temperature is reconstructed with different proxies. Some may record cave air temperature, some record a vegetation - temperature driven d13C, and others record atmospheric air temperature with d2H or CaCO3 d18O. The seasons that are recorded by the different proxies may have a large impact on the reconstructed temperature amplitude, it would be good to mention and discuss this in more detail.

This comment has been addressed in the Line 325 technical comment below.

Chapter 5.3. Nice overview of how speleothem chronologies could potentially be used as tuning targets for climate archives that lack absolute chronologies. I do believe that this chapter could benefit if the potential pitfalls would be described. Please caution against tuning between records over long distances that are not necessarily part of the same systems.

We now end that paragraph (line 764 of the revised manuscript) with a clarifying statement:

Yet even when such distant correlation is based on strong common drivers of distal signals, regional climate processes which are independent of the common processes may add additional variability to each record which complicates robust tuning. As more absolute dated speleothem records emerge, it will be possible to more rigorously evaluate the fidelity of these long-distance teleconnections on varying timescales.

Technical comments:

Line 12: should be "largest amplitude global climate"

Thank you. We have added the word 'global' to this sentence.

Line 15: "a sequence of feedbacks" does not seem correct as a feedback is a consequence of an event that reinforces (positive) or buffers (negative) the effects of the event itself. Maybe rewrite to: "the sequence of millennial events, their climate feedbacks and rates of change".

That's a good point. We have made this change.

Line 19: "and unlike proxies in other archives like ice or marine cores," I would delete this part. Ice cores over the world cannot be interpreted similar, for example if you compare a d18O ice from the Andes mountain range it may not be related to temperature as it is in the NGRIP ice core. Also marine sediments have proxies that may be interpreted differently around the world: In the Mediterranean d18O of surface dwelling foraminifera may be a P-E signal, whereas it might be dominated by temperature in regions where P-E is less dominant (polar regions?). I would rewrite it like this: "are encoded in a number of proxies, however, the climatic"

You are absolutely correct in the details. We would still like to flag the differences between marine and ice core d18O on the one hand and speleothem d18O on the other hand, particularly to researchers who are not from the speleothem field, and have clarified that we refer to **polar** ice core d18O-based temperature records and the **benthic foraminiferal** d18O-based sea level curves. In such records the d18O proxy, no matter the location, has the same overall interpretation, though of course subject to regional nuances. Whereas this is really not the case when it comes to speleothem d18O records. Speleothem d18O records from one location may track temperature-dependency of meteoric precipitation, and in another they may track source water changes. While we appreciate, and agree with you regarding the details, we would like to retain the wording that we currently have so that we can flag the larger differences.

Line 28: "maybe" should be "may be"

Thank you. We have made this correction.

Line 29: "IIA" should be "IIIA"

Thank you. We have made this correction.

Line 42: see comment on line 12

Thank you. We have made this change.

Line 51: see comment on line 15

Thank you. We have made this change.

Line 68: add reference "Lisiecki and Stern (2016)" they also use the EA speleothem record to tune the older part of the record.

Thank you. We have added this reference.

Line 143: "the timing temperature change," should read "the timing of temperature changes"?

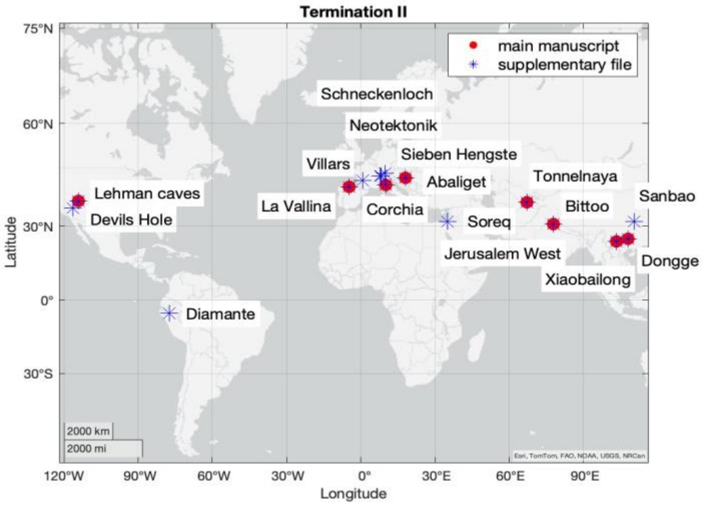
Yes! Thank you. We have made this correction

Line 143: temperature reconstruction can be provided by multiple proxies, such as fluid inclusions d2H (Affolter et al., 2019), calcite-water d18O with fluid inclusion and calcite d18O, TEX86 (Levy et al., 2023; Wassenburg et al., 2021) as well as (dual) clumped isotopes (Bajnai et al., 2020; Wassenburg et al., 2021).

Thank you. We have added these details and references to Section 2 as well.

Figure 1: To give the reader an idea of the total nr of Termination records, it would be good to include all available Termination speleothem records in Figure 1. This also gives the reader an idea of how many records have been excluded by using the author's criteria and assess potential (if any) biases towards certain records or regions. The prioritized records could be indicated with different symbols or color as the ones that were left out.

This is a good suggestion. We have made this change. The modified maps have also been given below.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Villars
Abaliget
La Vallina
Corchia
Soreq
Jerusalem West
Tonnelnaya
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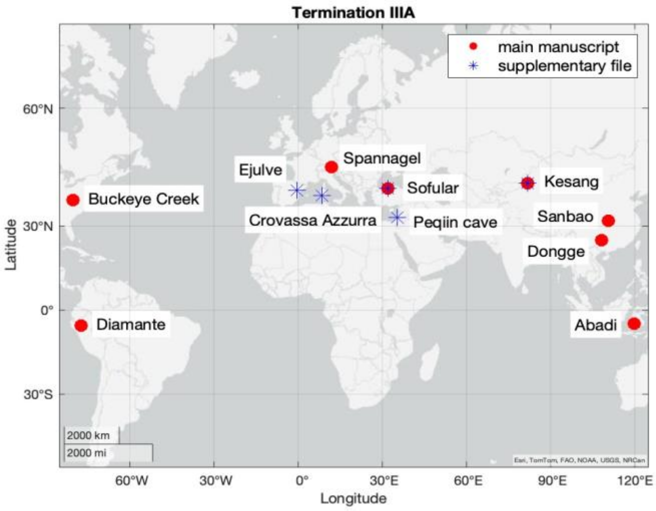
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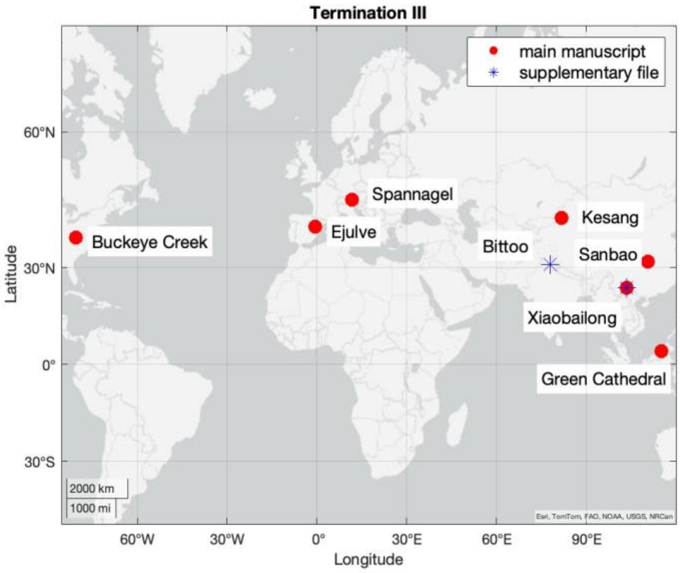
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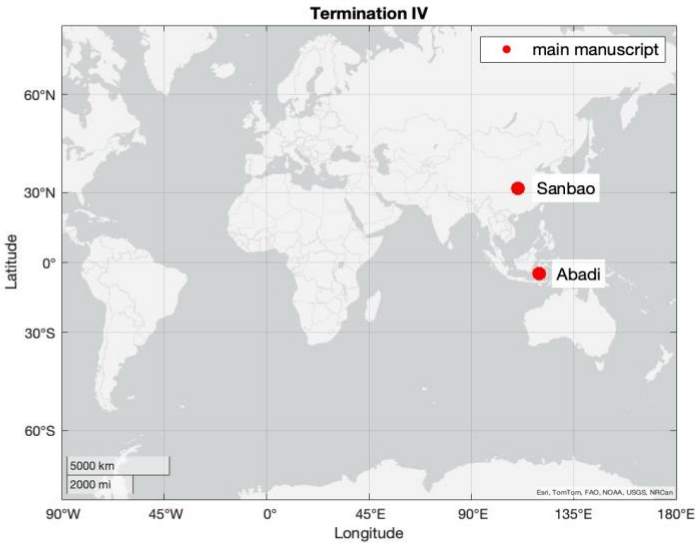
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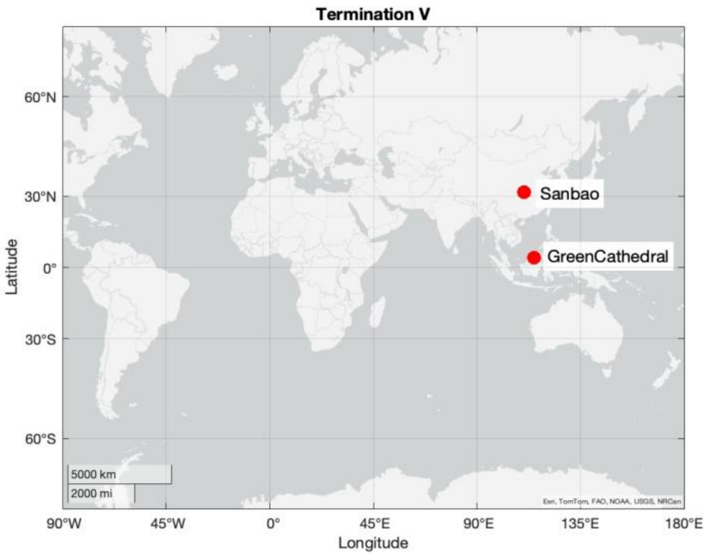
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Esri, TomTom, FAO, NOAA, USGS, NRCan

Line 174: better reference is “Fohlmeister et al. (2018)” which is speleothem specific instead of “Kim et al., 2007” even though the difference between calcite and aragonite is similar, i.e. 0.8 permille.

This is a good suggestion. We have added the reference to Fohlmeister et al, 2018 as well.

Fohlmeister, Jens, et al. "Carbon and oxygen isotope fractionation in the water-calcite-aragonite system." *Geochimica et Cosmochimica Acta* 235 (2018): 127-139.

Line 293: Provided that kinetic offsets from isotope equilibrium do not change.

We acknowledge that variation in oxygen isotopic fractionation (and the potential influence of PCP on oxygen isotopes) is under discussion. We feel that line 293 is not the optimal place to add this detail, since indeed this affects interpretation of all oxygen isotope records in speleothems not only those in regions sensitive to temperature effects. Therefore, we have raised this as a point in the comparison of calcite d18O with fluid inclusion d18O in line 387 of the revised manuscript:

Despite their lower temporal resolution, one advantage of fluid inclusion d18O measurements is that unlike d18O calcite records, the interpretation of fluid inclusion d18O does not require assumption of constant d18O water-calcite fractionation. The reliability of fluid inclusion analytical methods is improving with techniques to correct for analytical evaporation effects (Fernandez et al 2023).

Fernandez, A., Løland, M. H., Maccali, J., Krüger, Y., Vonhof, H. B., Sodemann, H., & Meckler, A. N. (2023). Characterization and correction of evaporative artifacts in speleothem fluid inclusion isotope analyses as applied to a stalagmite from Borneo. Geochemistry, Geophysics, Geosystems, 24, e2023GC010857. https://doi. org/10.1029/2023GC010857

Lines 303 - 304: See comment on lines 270 – 271.

We have now addressed this in lines 270-271.

Lines 307 - 309: Move to section 3.2. ice-volume corrections.

This is a good suggestion. Thank you. As detailed in the first comment, we would prefer to retain all corrections made to the records in Section 2.

Line 325 (and 343 – 345): Temperature is reconstructed with different proxies. Some may record cave air temperature, some record a vegetation - temperature driven d13C, and others record atmospheric air temperature with d2H or CaCO3d18O. The seasons that are recorded by the different proxies may have a large impact on the reconstructed temperature amplitude, which needs to be discussed.

This is a really good point. After the first sentence of 3.3, we have added

While multiple parameters are sensitive to temperature, because they capture the signal in different parts of the atmosphere-land surface-and cave system, they may record different seasons and therefore potentially also different amplitudes of temperature change. Cave temperatures, which in most settings reflect mean annual temperature, are recorded by TEX86 (Wainer et al, 2011;

Matthews et al, 2021; Nehme et al, 2020) and fluid inclusion microthermometry (eg Meckler et al, 2015). Oxygen isotopes measured in calcite or fluid inclusions and dD in fluid inclusions, will reflect the temperature influence on atmospheric processes but biased to the season contributing most to dripwater infiltration, which will vary by setting. For example, the Hungarian caves study by Demeny et al uses winter half year rainfall d2H-temperature relationship for reconstruction while using similar d2H methods, the Wilcox et al study from the Swiss Alps uses an annual rainfall d2H-temperature relationship. All the fluid inclusion oxygen isotope studies and the TEX86 study reconstruct annual average surface temperatures reflected by annual average cave temperatures (Wainer et al, 2011; Matthews et al, 2021; Nehme et al, 2020). The initial carbon isotopic ratio set by soil and vegetation processes may be recorded with seasonal bias if stalagmite deposition has a seasonal bias.

Line 394: At the Jiangjun cave site the amplitude was about 4-5 degrees C, which would correspond to max. 1 permille in calcite d18O. The 2 permille indicated in line 394 as a "temperature effect" is thus not correct. Instead, the additional 1 permille change was explained by a potential bias of the fluid inclusion d18O towards high intensity monsoon rainfall that affected the fabric and incorporation of the fluid inclusions through drip rates.

Thank you. We have made this correction to the text.

Lines 472 – 473: Would it be an idea to use a linear interpolation for the ice volume correction curves, such that you can maintain the original resolution of the speleothem isotope records, but still use an ice-volume correction?

We debated this as well. The age control of speleothems is stronger than the one for the ice volume correction records. Our decision to bin the records takes into account the records with higher age uncertainties.

I wonder if ordering the figures top down according to the timing of the "first response" to the glacial termination would be a better representation of the results. I do believe that it will be easier to read the figure as it would follow the same order as the records are mentioned in the manuscript.

This is what we have tried to do since we found it easier to follow as well.

Line 477: It already starts increasing around 140,000 yrs BP? What is the "starting point" of increasing insolation based on?

In each instance, we have based the 'starting point' at the start of the sharpest rise in insolation. This is at 137,000 years BP for Termination II.

Line 485: This should be coincident with the TII interstadial event, that is actually visible in quite a few EAM records as well as increased runoff in the bay of Bengal (Nilsson-Kerr et al., 2019).

Yes exactly! And as Nilsson-Kerr et al also find, we don't see this in the ISM Bittoo or Xiaobailong cave speleothem records and perhaps a muted signal in the Dongge record but observe a clear signal in the Hulu speleothem record.

5.2. Excellent chapter. The only discussion point you might want to add is that north Europe may be expected to show a cooling in response to freshening and AMOC shutdown, but this is not clear in the northern Europe d18O records.

Precisely because the northern Europe d18O do not consistently show this pattern, we decided not to introduce the "expected" response. One factor may be that the d18Osw influence is only corrected in the North European records for TII, as there is not yet a North Atlantic curve for earlier Terminations.

5.4. well done.

Thank you so much!

Chapter 6. Good future directions, well supported by the compiled speleothem Termination records.

Thank you again. We really appreciate the comments, feedback and discussion.

Best wishes,

Jasper Wassenburg

Affolter, S., Häuselmann, A., Fleitmann, D., Edwards, R.L., Cheng, H., Leuenberger, M., 2019. Central Europe temperature constrained by speleothem fluid inclusion water isotopes over the past 14,000 years. Science Advances 5(6), eaav3809. doi.org/10.1126/sciadv.aav3809.

Bajnai, D., Guo, W., Spötl, C., Coplen, T.B., Methner, K., Löffler, N., Krsnik, E., Gischler, E., Hansen, M., Henkel, D., Price, G.D., Raddatz, J., Scholz, D., Fiebig, J., 2020. Dual clumped isotope thermometry resolves kinetic biases in carbonate formation temperatures. Nat. Commun. 11(1), 4005. doi.org/10.1038/s41467-020-17501-0.

Levy, E.J., Vonhof, H.B., Bar-Matthews, M., Martínez-García, A., Ayalon, A., Matthews, A., Silverman, V., Raveh-Rubin, S., Zilberman, T., Yasur, G., Schmitt, M., Haug, G.H., 2023. Weakened AMOC related to cooling and atmospheric circulation shifts in the last interglacial Eastern Mediterranean. Nat. Commun. 14(1), 5180. doi.org/10.1038/s41467-023-40880-z.

Nilsson-Kerr, K., Anand, P., Sexton, P.F., Leng, M.J., Misra, S., Clemens, S.C., Hammond, S.J., 2019. Role of Asian summer monsoon subsystems in the inter-hemispheric progression of deglaciation. Nat. Geosci. 12(4), 290-295. doi.org/10.1038/s41561-019-0319-5.

Wassenburg, J.A., Vonhof, H.B., Cheng, H., Martínez-García, A., Ebner, P.-R., Li, X., Zhang, H., Sha, L., Tian, Y., Edwards, R.L., Fiebig, J., Haug, G.H., 2021. Penultimate deglaciation Asian monsoon response to North Atlantic circulation collapse. Nat. Geosci.(14), 937-941. doi.org/10.1038/s41561-021-00851-9.

Citation: https://doi.org/10.5194/cp-2024-37-RC1

RC2: 'Comment on cp-2024-37', Anonymous Referee #2, 09 Aug 2024

This is an interesting manuscript and a good start to stimulate further research on the timing and nature of Terminations. There is no doubt that speleothems have a great potential as they can be dated accurately and precisely with low age uncertainties. The manuscript tries to gather existing speleothem records in order to examine Terminations II, IIIA, III, IV and V in closer detail, with a focus on the sequence of events. I agree with the authors that a comprehensive overview on Terminations in speleothem is currently missing and this overdue. However, I have the feeling that the manuscript was put together quite hastily as the general structure is quite complex and many highly relevant figures are only provided as supplemental information and not in the main text (see comments below). I have the feeling that the authors should try to develop a more concise structure and to present their selection criteria for records more clearly. Furthermore, a more rigid statistical approach is required (see comments below).

Thank you for your comments on the relevance of such a study though we are sorry that you find the structure to be complex, that many figures are in the supplemental material, and that the selection criteria are not quite clear. We understand also that you would like to see a more rigid statistical approach. We will address your comments below and this will hopefully address these concerns.

Some parts on the interpretation of oxygen isotope values in section 2.1 should be moved to section 3. Furthermore, stronger emphasis should be given to the number of dates and sampling resolution of the selected key-records.

Section 2.1 gives only very concise interpretations as a justification for selecting the boundaries of different regions. The actual interpretations are elaborated in Section 3.

We fully understand your concerns regarding dates and sampling resolutions, especially given the nature of this study. That is why we have tried to balance the use of available records with uncertainties generated by low resolution records and those with poor age control. We had 2 choices with record selection, one was to select only the highest quality records at the risk of losing regions from the analysis, and the other was to consider the best records from the different regions with due consideration for their resolution (figures with low resolution records include sample points as markers where uncertainty grey bars are not available) and age control (all U-Th sample points and error bars for every record considered in the manuscript are shown in Figure 2 of the main manuscript and Supplementary Figure 1). We have gone with the second option. In addition to the more regular time series figures, Figure 7 explicitly highlights how the uncertainties in age control may be hindering our understanding of climatic events surrounding Terminations. We also provide uncertainty numbers in the text. Indeed, one of the goals of the manuscript is to highlight where records are available but could do with improvement in resolution and age control.

Many other speleothem records were not really considered in this overview, despite the fact that they could contribute some important additional information on the timing and nature of certain terminations. For instance the timing of the onset of stalagmite growth, e.g. the Sieben Hengste (Switzerland) record covering TII (Luetscher, M., Moseley, G.E., Festi, D., Hof, F., Edwards, R.L., Spötl, C., 2021. A Last Interglacial speleothem record from the Sieben Hengste cave system (Switzerland): Implications for alpine paleovegetation. Quaternary Science Reviews 262.) This record is very well dated and covers Termination II. Within the Alps, the Schafsloch record (Hauselmann et al., QSR, 2016) from Switzerland covering TII is not even mentioned in the text. There are also other speleothem records which could be useful and suited for this review, even if they cover only parts of a Termination. I think the authors should have done a more comprehensive review of the existing literature. Though some of the records are shown as supplemental figures, it appears that the selection of records in the main text is somewhat arbitrary. Furthermore, the fact that many important figures are shown in the supplemental information doesn't really increase the readability.

The Sieben Hengste record is indeed an excellent one. We have plotted the original record in the supplementary information and the ice-volume corrected record in the main manuscript Figure 4. Based on Reviewer 1's comments as well, we now also explicitly stated this in subsection 2.2. This may be confusion created because it was not plotted in Figures 1 and 2 or shown in Table 1. We are sorry about this. The figure was getting too crowded to show the Abaliget, Sieben Hengste and Schneckenloch records. Therefore, we show the Abaliget record which covers the whole Termination with reasonable resolution and age control (as per our record selection criteria) in Figure 2 along with its age control, and do the same for the Sieben Hengste and Schneckenloch records in the Supplementary Information. The Schafsloch record is a really nice one as well and one of the first covering this time period from the region. We were already showing the Abaliget, the Sieben Hengste and the Schneckenloch records from this region in the manuscript. The Schafsloch record is of excellent quality but covers a shorter time period than the 3 other records already in the manuscript, that is why, as per our sample selection criteria, this record has not been shown.

We believe that we have been as comprehensive as reasonably possible for this manuscript. SISALv3 is the largest speleothem database, and as mentioned in the manuscript, the database was built parallel to working on this project so that we have made every effort to track down speleothem records covering Termination TII through TV. We have mined the database systematically for any record within the Termination time periods and selected the most suitable ones (per our criteria given in the Methods section) for further discussion in the manuscript and Supplementary information.

The selection criteria of records are certainly arbitrary in the sense that it doesn't follow rigid criteria of a particular number of U-Th ages or a particular resolution. As we mention in the previous comment, we did this so that we could consider more records from more regions with due consideration for linked uncertainties.

We spent quiet a lot of time debating which figures should go in the main manuscript and which should go in the supplementary information. We would be happy to add more figures to the main manuscript perhaps also aided by the Editor's suggestions.

It remains unclear to what extent different age models (COPRA/Bchron/Stalage etc.) have an effect on the timing of Terminations and it would be useful to show the effects on 2-3 records in the main text. If the effects are minimal, then one can exclude at least on potential source of uncertainty.

This is a really good point, and as you say, merits more work. For example, Figure 2 in Perez-Mejias et al, 2017 highlights the difference in modeled ages based on two age depth models, OxCal and StalAge, even in records where the uranium-thorium ages have low uncertainties. In this case the authors have elected to use a mixture of age-depth model methods for creating the final age model. It is for nuances like this that we choose to use the author generated age models as a priority as long as the authors have provided uncertainty data.

Pérez-Mejías C, Moreno A, Sancho C, Bartolomé M, Stoll H, Cacho I, Cheng H, Edwards RL. Abrupt climate changes during Termination III in Southern Europe. Proceedings of the National Academy of Sciences. 2017 Sep 19;114(38):10047-52.

There is a non-trivial amount of analysis to be done using a function like change point and taking into consideration the uncertainties from all the age depth model ensembles. This work could also consider millennial events surrounding Terminations. This is work we hope to do in the future and has been listed in the future work section. That analysis is beyond the scope of this manuscript. In this manuscript, we take the first steps i.e. (i) plotting the U-Th sample points with their measured uncertainties, (ii) indicating some low-resolution records and (iii) showing uncertainties resulting from age-depth models on the figure (iv) author-generated or the same age models wherever possible to try and minimise uncertainties resulting from the use of different age-depth models.

A stronger consideration of carbon isotope records would be also useful, particularly for speleothem records from temperate regions where vegetation and soil microbial activity are highly dependent on temperature and rainfall. The full potential of the speleothem isotope records is not exploited

We agree with this comment. d13C is really an under-utilised proxy in speleothems. The limitation in including further records in these figures has been the availability of trace element or calcium isotope data to evaluate the PCP effects. We cite some excellent recent work making the most use of this proxy:

Genty et al, 2006

Lechleitner et al, 2021

Stoll et al, 2023

And we have added a point to the future work section as follows:

Speleothem d13C proxy records, particularly from temperate regions, are showing great promise in reconstructing past changes in temperature and rainfall when coupled with other proxies such as Mg/Ca and dCa. Such records from the particularly data dense Northern temperate regions would add great value to research on Terminations.

Is section 2.3 really necessary as no 13C record is shown in the current version of the manuscript.

We are sorry for this confusion. The d13C records are mentioned in section 2.3 and the degassing corrected version of the records have directly been plotted in Figures 4 and 6. The correction itself is shown in Supplementary Figure 3 which is creating this confusion. We will add the following sentence to the main manuscript Section 2.3. The Termination II La Vallina cave Garth speleothem record and the Termination III Ejulve cave Artemisa speleothem record $\delta^{13}C$ records have been discussed in the manuscript. These are indicated by the Y-axis label '$\delta^{13}C_{corr}$' in the figures.

The Figure 7 is not always correct. For instance, for TII, there is only one temperature increase in Europe, whereas the text states "final step of temperature increase in Europe and North America" (lines 644-645. Please make sure that Figure 7 is indeed conform with the main text. Furthermore, please make clear how the amplitude of the change was calculated. Ice volume correction applied. In this figure, one could also display insolation forcing to reveal the phasing more clearly.

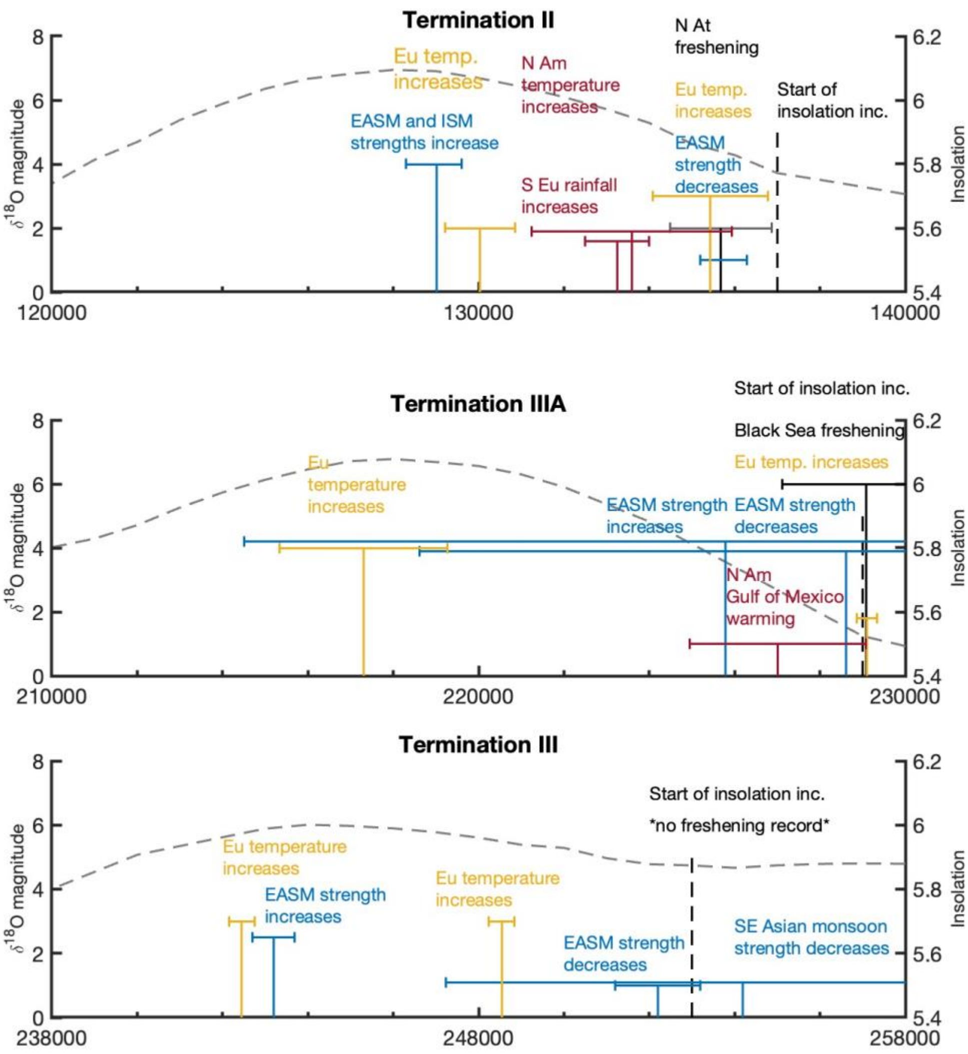
Thank you for spotting that. We have added the final step of temperature increase in Europe for Termination II now.

Figure 7 shows the amplitude as given in the individual Termination Figures 4, 5 and 6. And Figure 7 captures the climate changes from these figures that aid in the discussion of section 5.2. We have clarified this in the Figure caption now:

Figure 7: Sequence of **selected** global climatic events over Terminations. Ages and chronological uncertainties are represented on the X-axes. Amplitude of oxygen isotope changes that reflect the climatic events in speleothem records are plotted on the Y axes. **The amplitudes are taken from Figures 4, 5 and 6 for the respective Terminations.** The dashed line shows the start of insolation increase. [precip = precipitation; temp = temperature; N Eu = North Europe; S Eu = South Europe; N Am = North America; C As = Central Asia; ISM = Indian Summer Monsoon; EASM = East Asian Summer Monsoon; SE Asia = Southeast Asia; S Am = South America]

That’s a really good idea regarding insolation! We have added that curve to the figure.

Thank you for your suggestions on this figure. These changes will make the figure much clearer!



The effects of the "ice volume-correction" should be also shown more clearly as this is an important aspect as ice-volume corrections can affect the overall structure of Terminations.

This may again be a case where we have moved some of the figures to supplementary information. The different sea level curves and ice volume effects of the different Terminations have been plotted in Supplementary Figure 3. The impact of the different ice volume corrections on all the records used in the main manuscript have been shown in Supplementary Figure 4. In the main manuscript itself, we have opted to show only the main record figures. So that the uncorrected records are shown in Figure 2. And the ice-volume corrected records, where the corrections do indeed make a difference to the structure of the Termination, are shown in Figure 4 with the Y-axis labelled d18Ocorr.

Specific Comments:

Section 3.1 Records of surface ocean freshening: In this section, the Corchia Cave record should be also mentioned.

A careful comparison of the d18Osw (from foraminiferal d18O and Mg/Ca) and the d18O of Corchia stalagmites over the last deglaciation has shown that d18Osw is not the dominant control of Corchia d18O (Stoll et al., 2022), so we have not included it in this section. Thus, we retain the section as is and discuss the regional signal from Corchia.

Lines 120-121: What is the specific rationale behind the use of single records and not composite records? Composite records are considered to be more robust than individual records.
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Our rationale for not including composite records is written here. We have also included this in the manuscript since we certainly don't want to give the idea that composites are not useful. Composite records and stacks have been known to increase the robustness of records by strengthening regional signals versus drip-site specific noise and by expanding chronological control (e.g. Bajo et al., 2020; Fohlmeister, 2012; Koltai et al., 2017). We elected to use single records in most cases because they gave us more information on age control and measured $\delta^{18}O$ values without having to account for modifications made to either during the process of creating composites.