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 2.2 examines which ice volume corrections are available and how these corrections have been made. And 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 will add a sentence to Line 240 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 Figure 4. 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. 4).**

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 will add the following text to Lines 270:

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 propose to end that paragraph (line 690) 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 will add 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 will make 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 we will clarify 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 will make this correction.

Line 29: “IIA” should be “IIIA”

Thank you. We will make this correction.

Line 42: see comment on line 12

Thank you. We will make this change.

Line 51: see comment on line 15

Thank you. We will make 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 will add this reference.

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

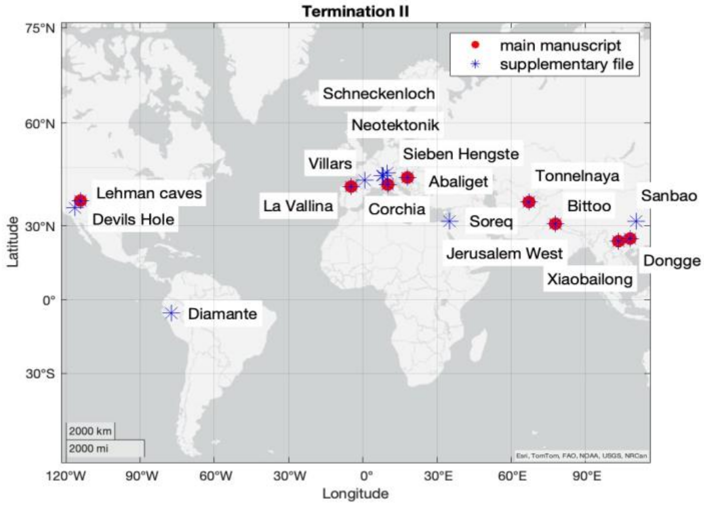
Yes! Thank you. We will make this correction

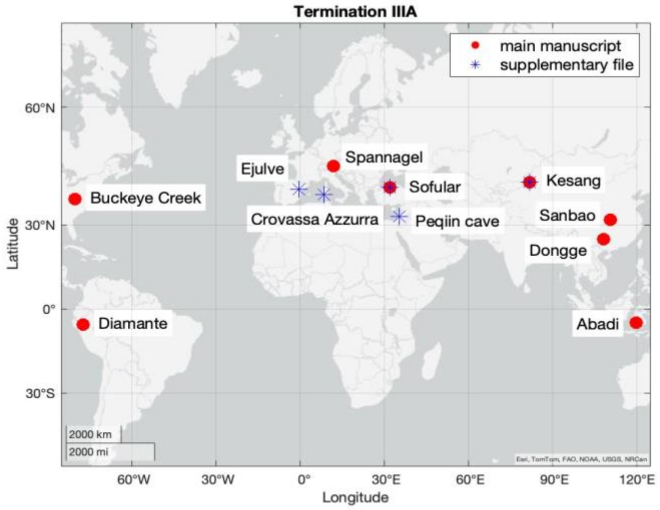
Line 143: temperature reconstruction can be provided by multiple proxies, such as fluid inclusions d2H (Affolter et al., 2019), calcite-water d18O with fluid inclusion and calcite d18O, TEX86 (Levy et al., 2023; Wassenburg et al., 2021) as well as (dual) clumped isotopes (Bajnai et al., 2020; Wassenburg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

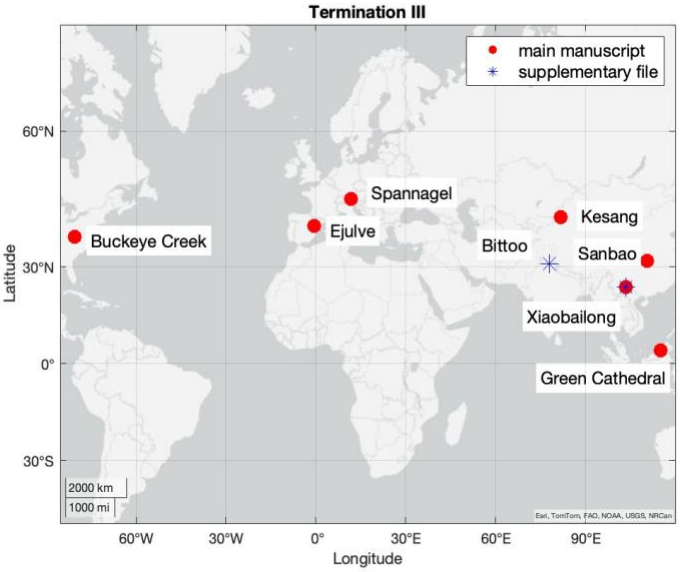
Thank you. We will add these details and references to Section 2 as well.

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 will make this change. The modified maps have been given below.



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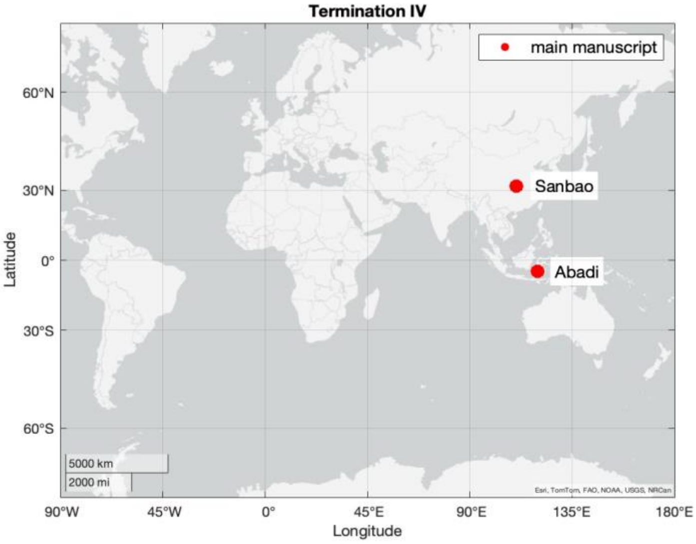
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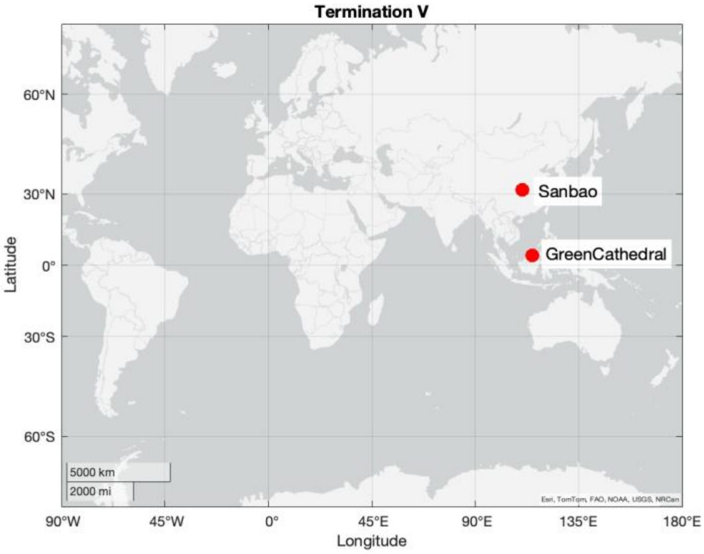
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Line 174: better reference is “Fohlmeister et al. (2018)” which is speleothem specific instead of “Kim et al., 2007” even though the difference between calcite and aragonite is similar, i.e. 0.8 permille.

This is a good suggestion. We will add 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 propose to raise this as a point in the comparison of calcite d18O with fluid inclusion d18O in line 334:

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 are now addressing 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 in Section 2. The last paragraph in Section 2.2. in the revised manuscript will now read as follows:

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 Figure 4. 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. 4).

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 would add

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 will make 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.

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