Reviewer comment 1

The manuscript by Endres et al. presents a high-resolution, Th/U-dated speleothem record from northwestern Iberia spanning 24-12 ka BP. The analyzed proxies are used to reconstruct North Atlantic surface ocean freshening ($\delta^{18}O$ values) and regional temperature changes ($\delta^{13}C$) during the last deglaciation. The authors identify major freshening events during Heinrich Stadial 1, and claim that the initial cooling response lagged the first meltwater pulse by approximately 850 years, suggesting evolving AMOC sensitivity to freshwater forcing. Overall, the study provides interesting new constraints on the temporal relationship between ice sheet meltwater discharge and Atlantic Meridional Overturning Circulation strength. The manuscript is overall well-written and the analytical methods are sound. Also the interpretation of the proxies is based on an intensive work of the research group in that area. However, I have some comments on the description of statistical aspects including propagation of uncertainties as well as the discussion of the regional relevance of the results. Overall, the line of arguments could benefit from restructuring the discussion by re-integrating parts of the extended appendices back into the main text. It is a bit exhausting to repeatedly having to switch back and forth between main text and appendix, also given that the main text is not so long.

Thank you very much for the assessment and the detailed review. We are happy to include your comments and suggestions to the final manuscript. Specifically, we will extend the description of the statistical aspects of the work in the sections outlined below. Following your suggestion, we will also extend / re-arrange / re-write the discussion section 3.5 Impacts beyond the North Atlantic Realm to include the information from the appendices.

Other comments:

1. **Age model.** The authors state that they have optimized the age model by using the Sr/Mg ratio in the stalagmite. Please discuss a little but further why this approach is valid at this coastal location, where one could expect a significant and varying influence of sea spray, that could affect the Sr/Mg ratio as well. Also provide more details what has been exactly done and how the age model has been optimized. Have you smoothed the Sr/Mg ratio prior correlation analysis with growth rate? What was the highest correlation coefficient? How does this approach influence the finally given uncertainties of the age model (and then, the uncertainties of the break/changepoints).

Thanks for the prompt to clarify this issue. We will extend the section 2.2 U-Th Dating and Age Model to address these questions, implementing the information given here below.

Related to using the Sr/Mg ratio:

The delivery of sea aerosols is insensitive to the changes in distance from the coast in the range between the current (43.5km from coast) and estimated glacial maximum distance (8 km from coast) of the cave (Kost and Stoll, 2023). Median modern dripwater Na concentrations in interior cave sectors where GLAS was collected are 5 ppm (Kost et al., 2023). For the minimum stalagmite Mg/Ca at 9 mmol/mol (DMg of 0.0225) this Mg from marine aerosols would constitute 3 to 6% of the dripwater Mg for open system dissolution in the range of 600 to 8000 ppmv CO_2, leading to variations in the dripwater Mg/Ca and Sr/Mg of about 3% between glacial and interglacial endmembers, a very small variation compared to the measured Sr/Mg range of 0.002 - 0.006 (a 40% increase) in this sample. Further, Sr/Mg ratio has shown to be covarying with growth rate also in other samples of the NISA archive (Sliwinski et al., 2023).

Related to the age model:

The age-depth model has been computed per the algorithm of Haslett and Parnell (2008) using the package BChron with 50'000 iterations and by explicitly providing the dating sample thickness as an additional constraint (as this is known because of our drilling method) and all samples have been assigned an outlier probability of 0.1. The age uncertainties stated in the paper are the 95% CI output of this statistical model and we refrained from further constraining these, thus this remains a conservative estimate. However, instead of using the statistical median model as our author age-depth model we have selected from the full ensemble of plausible age-depth model created by BChron the one model featuring the highest correlation with the Sr/Mg ratio, following the rationale outlined above. By selecting the alternative age model, abrupt changes in growth rate were mitigated and the pearson correlation coefficient between Sr/Mg and has improved from 0.27 (BChron Median model) to 0.60 (SrMg optimised Model).

We will provide a figure in the supplementary where the growth rate of the two age models can be compared directly.

Kost, Oliver, and Heather Stoll. "Marine aerosols in coastal areas and their impact on cave drip water–A monitoring study from Northern Spain." *Atmospheric Environment* 302 (2023): 119730.

Kost, Oliver, Saúl González-Lemos, Laura Rodríguez-Rodríguez, Jakub Sliwinski, Laura Endres, Negar Haghipour, and Heather Stoll. "Relationship of seasonal variations in drip water δ 13 C DIC, δ 18 O, and trace elements with surface and physical cave conditions of La Vallina cave, NW Spain." *Hydrology and Earth System Sciences* 27, no. 11 (2023): 2227-2255.

Sliwinski, J. T., Oliver Kost, Laura Endres, Miguel Iglesias, Negar Haghipour, Saúl González-Lemos, and Heather M. Stoll. "Exploring soluble and colloidally transported trace elements in stalagmites: The strontium-yttrium connection." *Geochimica et Cosmochimica Acta* 343 (2023): 64-83.

Breakpoints/Changepoints. The outcomes of the study rely strongly on statistical time series analysis and the correct propagation of uncertainties. It is however unclear to me, how the age model uncertainties have been propagated into the uncertainties of the break/change point analysis. The resulting change/breakpoints are also only given in a table. It would be beneficial to visualize the timing of the events in the stalagmite also in Figure 3.

Please also improve the quality of Figure 3, the discussed “drops” or other events in the $\delta^{13}C$ record are not visible in the Figure, possibly because the y axis is too small. Please improve and make it easier for the reader to follow your arguments…

Thank you for the comments and suggestion to clarify.

We will extend the explanation in the method section and will provide the Analysis R script in a public zenodo repository, to clarify that the age uncertainties have been propagated by conducting the Breakpoint analysis not only on the main age model but on the full BChron ensemble. As outlined above, our age model uncertainties are a conservative estimate and we are fully propagating the uncertainty here. This propagation makes the uncertainty of the changepoints relatively large, and thus, again, is a very conservative estimate.We will edit Figure three to enlarge the y axis for the d13C_init plot.

2. **Meltwater model results.** I am not a modeler and after reading the manuscript the relevance of the meltwater/tracer modeling is still unclear to me. I feel like the main conclusions could also be drawn without all this effort..? If I could follow the manuscript correctly, the model results are mainly part of the methods section, and there is only a limited discussion of model implications in the results/discussion. Could the results be helpful to explain a mechanism why there is a 850y lag between meltwater and temperature? Overall, the integration of the model results into the results/discussion section should be improved and the relevance clarified for non-experts in that field.

Thank you for your comments. and the suggestion to better integrate the way the modeling results improve understanding of the proxy record.

We propose to more clearly highlight throughout the discussion the aspects of the interpretation which are aided by the illustrated model experiments. One key takeaway from the model experiments is the documentation that under periods of stronger AMOC the freshwater d18O signal is quickly removed from the surface ocean, leaving a very weak fingerprint. This supports our interpretation that a significant freshening signal from MWP1a may not be salient in the stalagmite proxy record because of strong AMOC at this time.

Regarding model support for a delayed AMOC response to freshwater, we revise the discussion paragraph L.234-243 to provide a clearer theoretical background why a delay in the AMOC response is consistent with our theoretical understanding of AMOC stability, supported by published model results. One high resolution GCM model found AMOC collapse occurred 1750 model years after the onset of a gradually increasing North Atlantic freshwater forcing (van Westen and Dijkstra, 2023). Simulations in HadCM3 (Rome et al., 2025) under glacial boundary conditions exhibit lags and oscillatory response to a constant freshwater forcing. These are consistent with AMOC theory (e.g. Barker et al 2021). We will clarify that the dye trace models described in this manuscript do not explicitly investigate the time lag which is already discussed in the underlying simulations by Rome et al 2025.

van Westen, René M., and Henk A. Dijkstra. "Asymmetry of AMOC hysteresis in a state-of-the-art global climate model." *Geophysical Research Letters* 50, no. 22 (2023): e2023GL106088.

Romé, Yvan M., Ruza F. Ivanovic, Lauren J. Gregoire, Didier Swingedouw, Sam Sherriff-Tadano, and Reyk Börner. "Simulated millennial-scale climate variability driven by a convection–advection oscillator." *Climate Dynamics* 63, no. 3 (2025): 150.

Barker, Stephen, and Gregor Knorr. "Millennial scale feedbacks determine the shape and rapidity of glacial termination." *Nature Communications* 12, no. 1 (2021): 2273.

3. **"Regional/global discussion".** The comparison with other records is very limited and could be strengthened. On the regional scope, only 2 other speleothem records from Iberia and the Mediterranean are mentioned and only in the appendix. It is unclear to me why the discussion then only focuses on comparing to records from the EASM region, where the comparison then turns out to be not as conclusive (compare L296ff). I strongly suggest to revise this section, and focus on a more integrative approach comparing first to records from the wider North Atlantic realm in more detail. There are e.g., some high-resolution records from across the Americas (for example Travis Taylor et al., 2025, Strikis et al., 2015, and others) that are much closer to the centers of action in the North Atlantic. There are also probably some more from Western/Central Europe… (e.g., NALPS, Li et al., 2021, Luetscher et al., 2015, …). Incorporating more records from the wider Atlantic region could support the discussion of potential "atmospheric responses", that is at this stage only briefly mentioned in L252 or 290, but I regard this is as not irrelevant in this discussion. Also, in a subnote, I wonder about the absence of a drop into the Younger Dryas at the end of the record. I know this is not the focus of the manuscript but it still makes me wonder… Many other stalagmite records show a very sharp and clear drop in $\delta^{18}O$ values around 12.9ka BP (e.g., Cheng et al., 2020, Affolter et al 2019, Li et al., 2021 …) , but this one, that should presumably be very sensitive to meltwater and temperature in the north Atlantic realm, does not really show a clear signal, at least not in $\delta^{18}O$… What does this mean?

We thank the reviewer for prompting us to examine which records are included in compraison in the main text figure and the supplementary figure.

First of all, we will clarify in results, that the focus of interpretation on the new record is from the LGM through the early Bolling Allerod; by the onset of the Younger Dryas, stalagmite GLAS has a significant drop in growth rates, reducing significantly both the resolution of proxy data due to smoothing, and the precision of chronological constraints.

We will clarify in the discussion that we focus our comparison on the records which cover this full period (e.g. 20 ka to 14 ka) with comparable precision in chronology as the GLAS record. Because it is not the purpose of this paper to review and re evaluate the diverse factors encoded in global stalagmite d18O records nor assess the impact of AMOC on these processes, we also will clarify that we focus comparison on records from locations where a clear link with AMOC has been previously described through models, theory, or data, including during AMOC weakening : the cooling in western Europe (NALPS Speleothem (Li et al., 2021; Luetscher et al., 2015), the southward ITCZ migration in South America (Brazil Speleothem Paixao Cave (Strikis 2015):, and the East Asian monsoon response (already Hulu Cave shown in Figure 4). We hope that our new record will provide an important North Atlantic reference for future studies to test how atmospheric processes in other regions may be affected by AMOC, but such a discussion is beyond the scope of this paper.

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Minor comments along the text:

L65 Please provide more support that Sr/Mg is indeed only growth rate and not related to sea spray

We will extend section 2.2 to convey this information, as outlined in our reply to main comment 1.

Figure 2 What do the open and filled symbold mean? What is the correlation between Sr/Mg and growth rate?

We will add to the Figure caption for clarification: Open and filled symbols were chosen to simplify retrieving the width of a specific date on the age-depth axis by comparing with the purple estimates. The pearson correlation coefficient between Sr/Mg and growth rate is 0.6.

L171 does the number 382 years correspond to the length of the transition? Please indictae the timing and uncertainties in the Figure, it is hard to see for some of the breakpoints where they are exactly identified.

Thank you. We will add the breaks and midpoints to Figure 3.

L189 Also here, I am not sure which “smaller transient event” is meant. Possibly a second plot that zooms only into the most interesting section of the record would be helpful?

Following the suggestion of the 2nd reviewer we will update the nomenclature and name the events by their age midpoints. The “smaller transient event” will be named FE_16.45k, and as this indicated in Figure 3.

Figure 3 please include time markers of identified events in Figure 3. I also cannot see the temperature changes in d13C as mentioned in the text… The relevance of the maps in the uppermost panel are unclear to me.

Following the previous responses, we will add time markers and event names to Figure 3. We will also update the map to show ice sheet mass loss (like in the appendix) directly. We believe that this will improve the visual message that the key interest is in enhancing the understanding of melting from different ice sheet sectors.

L225 I cannot see a “significant cooling” in d13C at that time in Figure 3, I think the y-axis not large enough to really see this drop? A clear marker would be also helpful.

We will add a marker noting the event. We will also enlarge the y-Axis of d13C_init.

L226 what is the uncertainty of the 850 years?

We will provide an estimate for the uncertainty.

L231 Again, unsure to which specific feature this refers to

We apologize for the confusion and will provide the updated nomenclature with naming by event type and their midpoint. Thus, The cold event referred to here will be called TE_17.01k. This event will be annotated in Fig.3.

L245 I think its vice versa? First the meltwater, then 850 years later the temperature drop?

Thank you for the request for clarification. The final paragraph of this section discusses the relationship of the abrupt cold event to the following freshening event (FE_16.1k). Similarly to above we believe that by providing a more straight forward nomenclature, the text should become more clear.

L276 The “extended discussion” only discusses two other records from Iberia and the Mediterranean, and no ice core records.

We agree that “extended discussion” is misleading here and will remove the annotation in brackets. As discussed in our reply to main comment 3, we will be adjusting which records are compared in the main text vs the extended discussion/supplementary, to compare our record to a larger body of records that have independent age control and have been previously interpreted as (indirect) AMOC strength indicator.

L278 Before jumping to the EASM I would have expected a more comprehensive comparison to other records that are more closer to the North Atlantic realm. Is there a We specific reason why this is missing?

We appreciate the suggestion to clarify the justification for the records included as comparison in Figure 3 and Figure 4. e will explicitly state our criteria at the onset of the discussion. We use Figure 3 to illustrate the North Atlantic records relevant to discussion of the Freshening signal. This figure includes results from sediment cores in the North Atlantic region. These provide an important context although lacking precise absolute chronology. The figure also presents Ice sheet model Glac-1D, which is constrained by observations of the Northern Hemisphere ice sheet and provides relevant context We believe this figure compiles the essential North Atlantic records relevant to interpreting the freshening. As discussed in response to a previous comment, we will provide an alternate set of maps focusing on ice sheet mass loss.

We clarify that the focus of Figure 4 and the resulting discussion, is a focus on the chronology and phasing and therefore includes the relevant records which feature high temporal resolution and an independent absolute age model, comparing regions where the global consequences of AMOC decline have been described. As described in our response to main comment 3, we focus comparison on records from locations where a clear link with

AMOC has been previously described through models, theory, or data, including during AMOC weakening : the cooling in the North Atlantic and western Europe (NGRIP ice core already shown, NALPS Speleothem (Li et al., 2021; Luetscher et al., 2015), the southward ITCZ migration in South America (Brazil Speleothem Paixao Cave (Strikis 2015), the East Asian monsoon response (already Hulu Cave shown in Figure 4), and the atmospheric CO2 rise hypothesized to respond to the Southern Ocean warming during AMOC weakening via a thermal bipolar see saw. Thus Figure 4 will compare:

- Greenland Ice Core (NGRIP)
- WDC CO2
- EASM: Speleothem Hulu YT
- Brazil Speleothem Paixao Cave (Strikis 2015):
- NALPS Speleothem (Li et al., 2021; Luetscher et al., 2015)

,Because changes in ocean circulation hamper assumption about reservoir ages and thus make sediment cores considerably more age uncertain, we are considering them as not suitable for the changepoint analysis in Figure 4.

In contrast, we will mention in the main text, but keep In the supplementrary other available records from N Spain, namely OST2 from Ostolo Cave (Bernal-Wormull et al.,2021) and also Maat from Meravelles Cave. Due to the respective cave systems, d18O in those records is likely more affected by changes in temperature and moisture availability. Because of this added layer of complexity, we considered having these records in the main text would not help our story, thus have put them to the supplementary. We will state this more explicitely in our main text and refer to the supplementary figure.

L290 Any suggestions which “atmospheric patterns”? A more comprehensive discussion could elucidate this possibly?

We will clarify that this sentence continues the discussion of the Westerly Jet from the previous sentences.

L292 This is also another reason why records from that region would be worth to compare with!

We agree that the Cave Without Name record (Feng et al) which records freshwater addition to the Gulf of Mexico, would be interesting to discuss. Unfortunately, this record has a nearly 2 ky hiatus during H1 and would not be included in Fig. 4, but we can use it to provide additional context in the dicussion of Figure 3.

L299 It would be interesting to see if the American records are better to compare with? Studies have suggested a close link to AMOC and NA temperatures - your record could provide the possibility to test this (compare eg Travis Taylor et al., 2025,Warken et al., 2020…)

We will clarify the rationale for which records are included and not in the comparison. We have added to the comparison the record from Brasil (Strikis et al 2015). In other regions of North America and the Caribbean, there are multiple and complex factors contributing to the d18O variability and we consider it beyond the scope of this paper to review and re evaluate the diverse factors encoded in global stalagmite d18O records. Therefore, we hope that our new record will provide an important North Atlantic reference for future studies to test how atmospheric processes in other regions may be affected by AMOC, but such a discussion is beyond the scope of this paper.

As we highlight in our response to main comment 3, we focus on records spanning the full LGM-14 ka period; The work by Travis-Taylor only spans a short section of our record, so is not considered for comparison here.

L301 what is the uncertainty of the ice record here?

The ice core record is based on the WD2014 chronology (Sigl et al., 2016). The age uncertainty in this time interval is better than 1% of the age, thus smaller than 200 years. We will add this information to the sentence in line 301.

L402 Heading does not fit to content, its only one record also from Iberia discussed

We will change the heading to A5 Comparison with Other Iberian Speleothem Records

References

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